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PROCRU: A Model for Analyzing Crew Procedures in Approach to Landing

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Table of Contents

List of Tables

Tables (cont.)

List of Figures

PREFACE

The work reported here was performed under NASA-Ames Research Center Contract Number NAS2-10035. Technical Monitor was Dr. Renwick E. Curry.

Dr. Carl Feehrer of BBN made a major contribution to the time-line analysis and development presented in Chapter 2. We also wish to acknowledge the valuable assistance provided during formulation of the time-line by Capt. Leonard Poor (Delta Airlines) and First Officer Oliver Kuronen (FO, Northeast Airlines, Ret.). Finally, we wish to thank Mr. Emmett O'Hare of the Air Transport Association for his assistance in obtaining flight manual information.

SUMARY

A model for analyzing crew procedures in approach-to-landing is developed. The model employs the information processing structure used in the Optimal Control Model and in recent models for monitoring and failure detection. Mechanisms are added to this basic structure to model crew decision-making in this multi-task environment. Decisions are based on probability assessments and potential mission impact (or gain). Sub-models for procedural activities are also included. Where these procedures affect aircraft responses or the information state of the crew, the effects are accounted for explicitly; where they affect sub-system operation, only the attentional load they impose is considered. Procedures can be interrupted and finished subsequently, or not completed at all, based on decisions made by the model. However, this initial implementation of the model does not permit procedural steps to be skipped over or reordered.

The model distinguishes among external visual, instrument visual, and auditory sources of information. The external visual scene perception models incorporate limitations in obtaining information. The auditory information channel contains a buffer to allow for storage in memory until that information can be processed.

Though parts of the model have been validated experimentally, no validation claims can be made for the complete model or all of its parts. In addition, some important aspects of human behavior (such as fault diagnosis of "trouble shooting", errors in discrete actions, or the effects of stress or social pressures in the cockpit) are not modelled, except by direct assumption.

Computer results are presented to illustrate the operation of the model. The effect on model predictions of some assumptions concerning crew activity and/or scenario factors are also explored.

1. INTRODUCTION

This report summarizes the results of efforts in Contract NAS2-10035 for the NASA-Ames Research Center to "Analyze and Model Flight Crew Procedures in Approach to Landing." The objectives of this contract were to analyze the functions and responsibilities of the crew in nominal, Category I ILS approaches (of a 727) and to develop an analytic/computer model for the task that could be used to explore the effects of flight crew procedures and other critical factors on performance and safety.

Chapter 2 of the report presents the results of the task analysis. The analysis was based on a detailed examination of flight manuals and discussions with flight personnel. A time-line was developed showing the activities of each member of the crew keyed to location in the nominal approach profile and "triggering events." The time-line is not intended to reflect the specific procedures of any air carrier but is, instead, an amalgamation that attempts to capture the significant aspects of the various procedures used. These results were reported earlier in an interim report [1]. They are repeated here, with minor modifications, for the reader's convenience.

In Chapter 3, we describe the model for the crew in the approach-to-landing task that was developed (called PROCRU for

Procedure Oriented Crew Model). As the name implies, the model is procedure oriented. However, it also emphasizes information processing and decision making aspects of human performance. Briefly, each crew member is assumed to have a set of "procedures" or tasks to perform. The procedures include both routines established "by the book" (such as checklists) and tasks to be performed in some "optimizing" fashion (such as flying the airplane). The particular task chosen at a given instant in time is the one perceived to have the highest expected gain for execution at that time. The gain is a function of mission priorities and of the perceived estimate of the state-of-the-world at that instant. This estimate is based on monitoring of the displays, the external visual scene and auditory inputs from other crew members. PROCRU draws heavily on the concepts and submodels of the Optimal Control Model for the human operator [2] for its information processing and control representation. However, there are many novel aspects and features of the model that constitute new developments.

Chapter 4 contains a detailed description of the specific procedures defined in PROCRU. The functions used in calculating the gain for selecting procedures as well as the "recipes" for the procedures are presented.

In Chapter 5, results illustrating the operation of PROCRU are presented. Sensitivity to system parameters and to operator parameters is examined.

The last chapter contains some recommendations for further investigation with PROCRU and for extensions of this initial implementation.

2. TIME-LINE ANALYSIS

In this chapter we present the results of a task analysis conducted to define the primary activities of each crew member, the "triggering events" associated with these activities, and the major flight milestones occurring along a category I raw-data ILS approach.* Since the sequencing of all of these time-line activities are dependent on the particular approach flown, a subsidiary goal of the analysis was to define an idealized "nominal" radar-vectored vehicle trajectory, representative of this type of ILS approach; the resulting trajectory parameter time-histories are thus also presented in this chapter.

Our goal here has been to develop a broad characterization of the procedures required for conducting raw-data category I ILS approaches. To this end, we have attempted to favor a composite of crew tasks and activities identified in the formal publications of different U. S. carriers, reported on in other studies of flight management during approach and landing, and obtained from discussions with personnel representing the three crew positions (Captain, First Officer, and Second Officer) of a 727. We believe that the resulting representation, while not directly representing a specific carrier under perfectly realistic conditions,

* 200' decision height (DH) and 2400' runway visual range (RVR).

successfully portrays the major elements of flight management needed for the modelling effort.

Section 2.1 below defines the nominal approach trajectory, and identifies the basic procedures associated with flight path control. Section 2.2 concludes the chapter with a time-line analysis of both a standard and monitored ILS approach, and a definition of general missed approach procedures. For the reader's convenience, a glossary of symbols and mnemonics is provided in Appendix A.

2.1 Nominal Approach Trajectory

Vehicle ground track is shown in Figure 2.1. The reference coordinate system is the local geographic navigation frame (north, east, and down), with the origin located at the effective glide slope transmitter location. For convenience in analysis, it was assumed that the runway (and localizer center line) is aligned along the east-west direction, and that the runway and surrounding terrain are at sea level.

The figure shows down range and cross-range distances, measured from the glide slope transmitter. Specific points along the ground track are tagged by time-to-go (time-to-touchdown) values, and correspond with specific flight milestones to be described shortly.

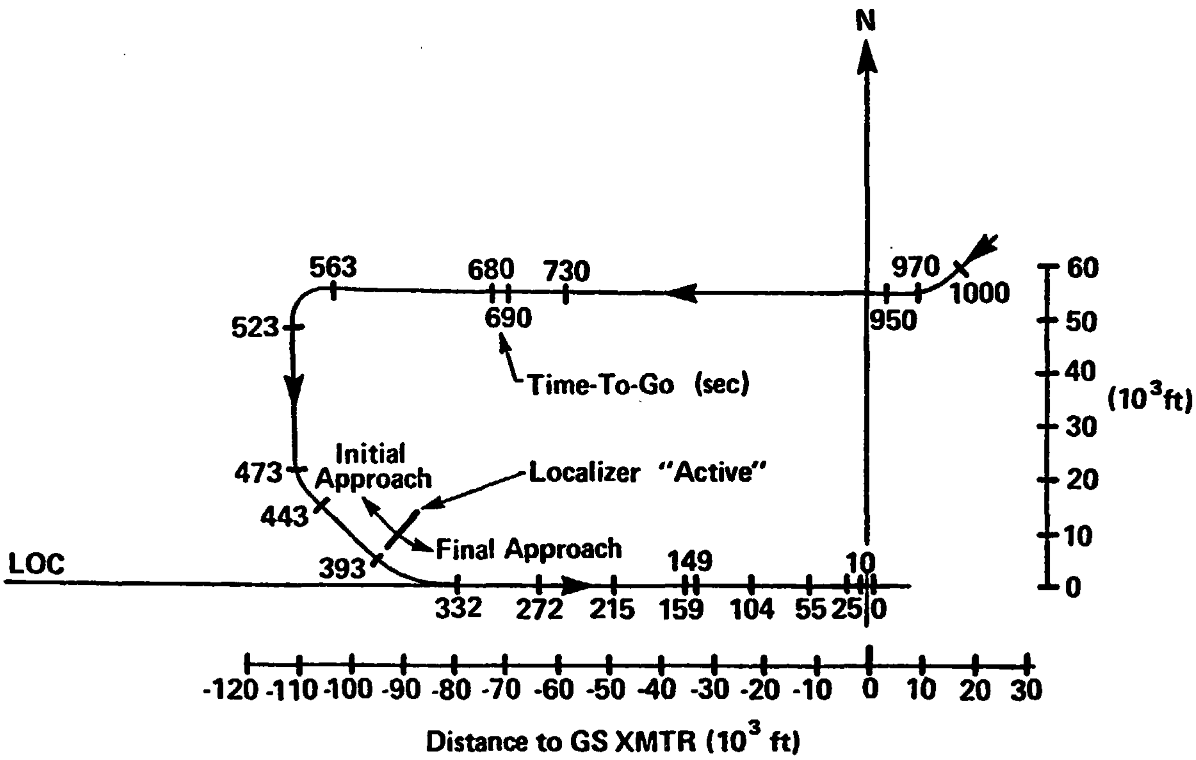

Figure 2.1. Vehicle Ground Track

The altitude, velocity, and heading profiles associated with this trajectory are given in Figure 2.2. Since the runway and surrounding terrain are at sea level, altitude and height above field elevation (AFE) are equivalent. Since no wind is assumed present, velocity and airspeed are likewise equivalent.

The vehicle is assumed to be radar vectored to the point at which the localizer becomes "active", following which final approach procedures are used to touchdown. As noted in Appendix B, it is assumed that a 2 dot localizer error (2 deg off final) will initiate HSI activity; the point of Figure 2.1 tagged t_{go}=393 thus conveniently separates the approach into an initial portion (before localizer activity) and a final portion (after localizer turn on). The next two sections provide details regarding these two approach phases.

2.1.1 Initial Approach

At the beginning of the initial approach, the vehicle is at 10000 ft, and travelling at 190 kts on a 210 deg heading; by the end of the phase the vehicle has descended to 2000 ft and slowed to 160 kts, and attained a 120 deg intercept course with the localizer approximately 16 nm from the field. This is accomplished with two descents, two decelerations, and three heading changes. Specific assumptions regarding this initial phase trajectory are as follows:

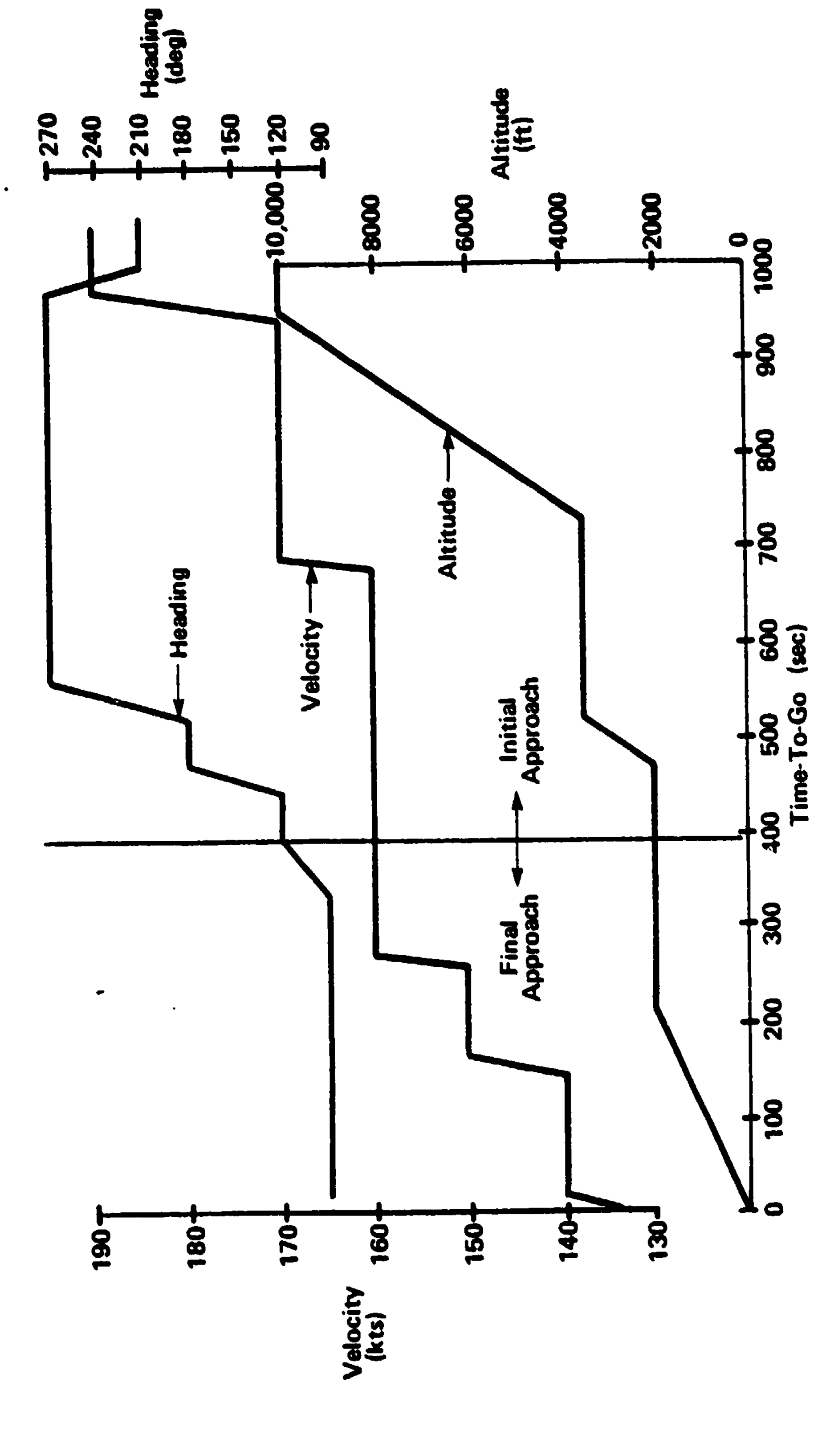

Figure 2.2: Altitude, Velocity, and Heading Profiles

1. Altitude, velocity, and heading changes are in direct response to ATC requests, and are accomplished in an accurate and timely manner.

2. The initial descent from 10000 ft to 3500 ft is made with an 1800 fpm sink rate; the second descent from 3500 ft to 2000 ft is made with a 900 fpm sink rate.

3. Both decelerations (from 190 kts to 170 kts to 160 kts) are made at a constant rate of 1 kt/sec.

4. All three heading changes assume a 3 deg/sec turn rate (two-minute turns), and assume 5 sec maneuver times for both rolling into and out of the turn.

2.1.2 Final Approach

At the beginning of the final approach phase, the vehicle is at 2000 ft, and travelling at 160 kts on a 120 deg heading; the end of this phase is defined by touchdown.

As noted earlier, it is assumed that the localizer becomes "active" when the vehicle is 2 dots off the localizer plane. This event signals the start of this final approach phase, and triggers a 0.5 deg/sec turn from the initial 120 deg heading to the final approach heading of 90 deg. Completion of the turn (at t_{go} = 332 sec) occurs as the vehicle intercepts the localizer plane. The vehicle then proceeds on a constant altitude (2000 ft), constant speed (160 kts) course until the glide slope becomes "active" . As noted in Appendix B, this occurs when the vehicle is 2 dots below the glide slope (at t_{go}=272 sec as shown on Figure 2.1).

The remainder of the final approach trajectory is shown in more detail in Figure 2.3. This localizer plane view shows specific trajectory points tagged with a triplet indicating time-to-go, altitude, and airspeed, and illustrates a standard approach based on the following assumptions:

<u>Environment</u>

1. The runway and surrounding terrain are at sea level.
2. No winds or gusts are present.

<u>Geometry</u>

3. The glide slope and runway geometries are those described in Appendix B.
4. The glide slope becomes "active" at 2 dots below the glide slope.
5. The middle and outer markers are 0.67 nm (4000 ft) and 5.3 nm (32000 ft) from runway threshold, respectively.

<u>Vehicle/Configuration</u>

6. Vehicle gross landing weight is 150,000 lbs.
7. A 30 deg landing flap setting is chosen.

<u>Procedure</u>

8. A 1 kt/sec deceleration to 150 kts is initiated when the glide slope becomes active (t_{go} = 272 sec).
9. An 8 fpm sink rate is initiated 1/2 dot below the glide slope (t_{go} = 215 sec).
10. A 1 kt/sec deceleration to 140 kts is initiated 10 sec before glide slope intercept (t_{go} = 169 sec).
11. Stabilization on the glide slope, at the approach speed of 139 kts, is achieved at the outer marker (t_{go} = 149 sec).

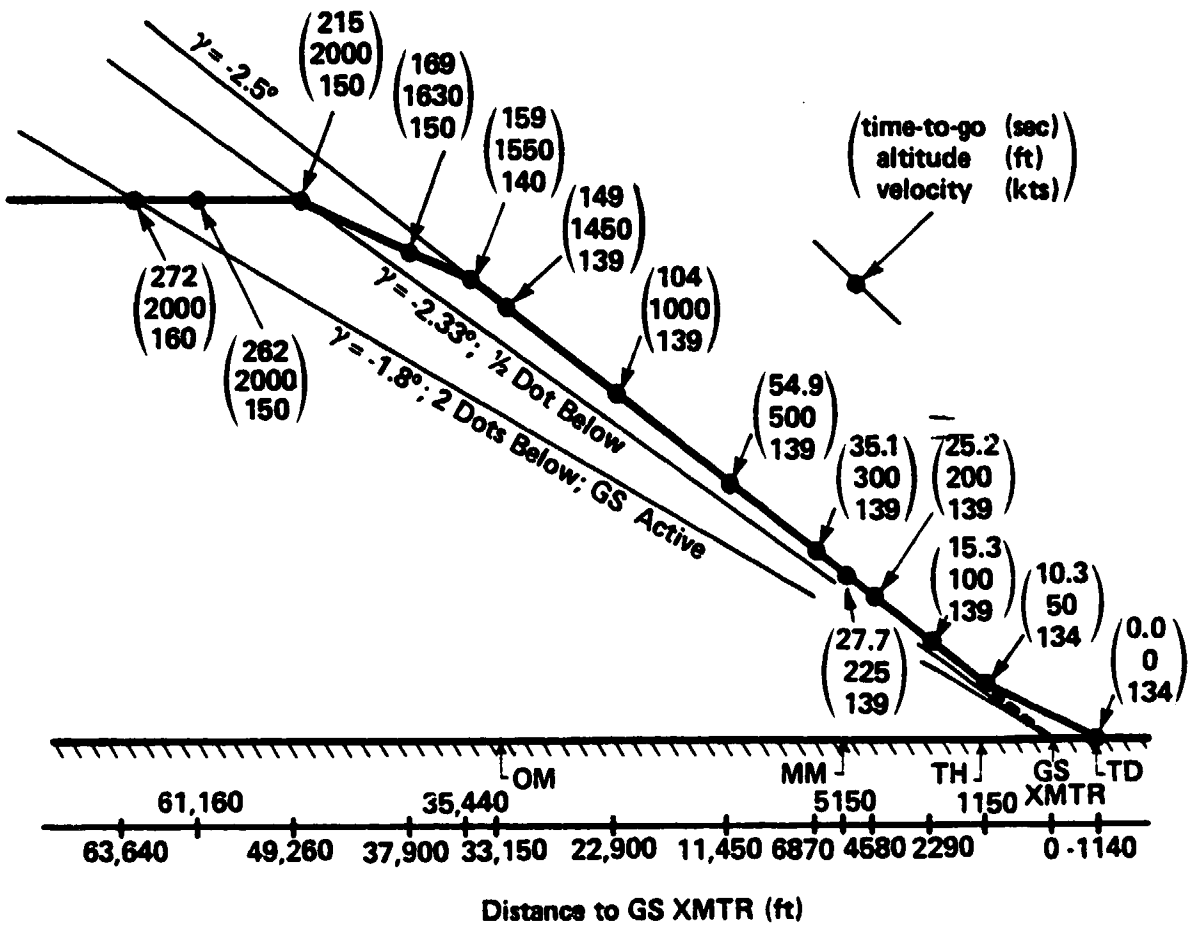

Figure 2.3: Final Approach Trajectory

12. A 1 kt/sec deceleration, to the threshold speed of 134 k' ., is initiated 5 sec before threshold crossing (t_{go} = 15 sec).

13. A flare to touchdown is initiated at threshold crossing (t_{go} = 10 sec).

Items 11 and 12 above assume a bug speed (VBUG) of 134 kts is chosen, on the basis of the reference speed and landing flap procedural rules defined by Tables 2.1 and 2.2, and on the basis of items 6 and 7. In addition, items 11 and 12 assume the approach speech (VAPP) of 139 kts and the threshold speed (VTHRESH) of 134 kts are chosen on the basis of the airspeed selection procedures summarized in Table 2.3, and on the basis of item 2.

2.1.3 Trajectory Variables

Time histories of the important trajectory variables are given in Table 2.4; the mnemonics associated with each variable are defined in Table 2.5. For convenient reference, the trajectory variables of Table 2.4 have been augmented with time histories of ATC requests, and a number indexing scheme has been used to relate these requests to the corresponding crew/vehicle responses (for example, ATC request number 3 at t_{go}=1000, "descend to 3500 ft", is followed by a descent initiation at t_{go}=950). In addition, important trajectory "events" have been tabulated, to show the relation between these events and major trajectory changes.

Table 2.1: Reference Speed (VREF) vs. Gross Weight (GWT)

GWT (10^3 lbs)	VREF (kts)
110	108
120	113
130	119
140	124
150	130
160	136
170	141
180	147
190	153

Table 2.2: Landing Flap Setting (LFLAP) vs. Bug Speed (VBUG)

LFLAP (deg)	VBUG (kts)
30	VREF + 4
40	VREF

Table 2.3: Approach/Threshold Speed Determination

VWIND		VGUST	VAPP	VTHRESH
≤ 10	and	0	VBUG+5	VBUG
> 10	or	> 0	VBUG+VWIND/2+VGUST	VBUG+VGUST

Note 1: all speeds in kts

Note 2: Maximum allowable value of VAPP is (VBUG+20)

Table 2.4: Time Histories of Important Trajectory Variables

ATC REQUESTS	(sec) TGO	(kts) V	(ft) A	(deg) H	(ft) RX	(ft) RY	(ft/s) V	(deg) G	(ft/s) ADOT	(sec) DTGO	(ft) DA	(ft) DR	THR	GEAR	(deg) FLAP	EVENTS
	0	134	0	90	+1140	0	223.3							D	30	TD
								-1.2	-4.9	10.3	50	2290				
	10.3	134	50	90	-1150	0	223.3						A		30	Cross TH
								-2.5	-9.9	5.0	50	1140				
	15.3	139	100	90	-2290	0	231.7								30	100' AFE
								-2.5	-10.1	9.9	100	2290				
	25.2	139	200	90	-4580	0	231.7								30	200' AFE (DH)
								-2.5	-10.1	2.5	25	570				
	27.7	139	225	90	-5150	0	231.7								30	Cross MM
								-2.5	-10.1	7.4	75	1720				
	35.1	139	300	90	-6870	0	231.7								30	300' AFE
								-2.5	-10.1	19.8	200	4580				
	54.9	139	500	90	-11450	0	231.7								30	500' AFE
								-2.5	-10.1	49.5	500	11450				
	104.4	139	1000	90	-22900	0	231.7								30	1000' AFE
								-2.5	-10.1	44.6	450	10250				
	149.0	139	1450	90	-33150	0	231.7								30	Cross OM
								-2.5	-10.1	10.0	100	2290				
	159.0	140	1550	90	-35440	0	233.3						A		25→30	on GS
								-1.9	-7.9	10.2	80	2460				
	169.2	150	1630	90	-37900	0	250.0						A	D	25	slow down
								-1.9	-8.1	45.5	370	11360				
	214.7	150	2000	90	-49260	0	250.0							U→D	25	1/2 dot below GS
								0	0	47.6	0	11900				
	262.3	150	2000	90	-61160	0	250.0						SLF	U	15→25	
								0	0	9.6	0	2480				
	271.9	160	2000	90	-63640	0	266.7						A		15	GS active (2 dot below)
								0	0	60.1	0	16030				
	332.0	160	2000	90	-79670	0	266.7								15	on LOC, end turn
								0	0	60.9	0	31020				
	392.9	160	2000	8 120	-95178	4155	266.7								15	LOC active, begin turn
								0	0	50.1	0	13360				
	443.0	160	2000	120	-106748	14990	266.7								15	end turn
								0	0	30.0	0	8000				
	473.0	160	2000	7 180	-110568	21610	266.7						SLF		15	2000' AFE, begin turn
								-3.2	-15.0	100.0	1500	26630				
8:HC=90@LOC	523.0	160	6 3500	180	-110568	48240	266.7						SFI		15	end turn, begin descent
								0	0	40.0	0	10668				
5:HC=180	563.0	160	3500	5 270	-103776	55031	266.7								15	begin turn
6:AC=2000								0	0	117.0	0	31200				
7:HC=120@ A=2000	680.0	160	3500	270	-72576	55031	266.7						SLF		15	
								0	0	10.0	0	2750				
4:VC=160	690.0	4 170	3500	270	-69826	55031	283.3						A		15	slow down
								0	0	40.0	0	11332				
	730.0	170	3500	270	-58494	55031	283.3						SLF		15	end descent
								-6.0	-29.5	220.0	6500	61985				
	950.0	170	3 10000	270	+3491	55031	283.3						SFI		5→15	begin descent
								0	0	20.0	0	6000				
1:HC=270	970.0	2 190	10000	270	+9491	55031	316.7						A		5	end turn, slow down
								0	0	30.0	0	9500				
2:VC=170 3:AC=3500	1000.0	190	10000	1 210	-17347	59567	316.7								5	begin turn

Table 2.5: Definitions of Symbols

TGO :	time-to-touchdown (sec)
V :	airspeed (kts or ft/sec)
A :	altitude (ft)
H :	heading (deg)
RX :	east-west ground-track range to GS XMTR (ft)
RY :	north-south ground-track range to GS XMTR (ft)
G :	flight path angle (deg)
ADOT:	altitude rate (ft/sec)
DTGO:	time interval between TGO markers (sec)
DA :	change in altitude over DTGO interval (ft)
DR :	change in distance along ground-track over DTGO interval (ft)
THR :	throttle (A = adjust; SLF = set for level flight; SFI = set to flight idle)
GEAR:	landing gear position (U = up; D = down)
FLAP:	flap setting (deg)

2.2 Time-Line Analysis

To provide a qualitative and quantitative description of crew activity during approach-to-landing, we conducted a time-line analysis of crew procedures. Our effort centered on the baseline trajectory described in the previous section, and presumed ATC radar vectoring to an ILS final. Glide slope and localizer geometries were assumed to be those described in Appendix B. Flight path management requirements (e.g., velocity, altitude, and heading transitions) were taken from the previous section, as were the procedural assumptions regarding transition characteristics (e.g., deceleration rates, sink rates, and turn rates).

In addition to these flight management requirements, the time-line analysis assumed additional procedural requirements imposed on the crew. The callout requirements assumed for the pilot flying (PF) and pilot not flying (PNF) are given in Tables 2.6 and 2.7. Requirements for verbal requests by the PF are also given in Table 2.6.

Included among the procedural elements in the time-line are three checklists typically required to be completed between 10,000 ft and the OM. Summaries of items assumed to be contained in each of the checklists are presented in Table 2.8.

Table 2.6: PF Requests/Callouts

Condition	Request/Callout
<u>Flap Requests</u>	
airspeed 170 kts	"Flaps 15"
airspeed 150 kts	"Flaps 25"
stabilized on GS	"Landing Flaps"
<u>Gear Request</u>	
1/2 dot below GS	"Gear Down"
<u>Callouts</u>	
Cross OM	"Outer Marker"
After OM	"DH is _____"

Table 2.7: PNF Callouts

Condition	Callout
<u>LOC/GS activity</u>	
LOC "active"	"localizer capture"
GS "active"	"glide slope alive"
<u>Approach Stabilization</u>	
$v > v_{app} + 10$ or $v < v_{app}$	"speed ______ kts $\left\{\begin{matrix}\text{high}\\ \text{low}\end{matrix}\right\}$"
$E_{LOC} > 1/3$ dot	"_____ dot $\left\{\begin{matrix}\text{left}\\ \text{right}\end{matrix}\right\}$"
$E_{GS} > 1$ dot	"_____ dot $\left\{\begin{matrix}\text{high}\\ \text{low}\end{matrix}\right\}$"
$\dot{h} > 2000$ fpm and $1000' < h \leq 2000'$ AFE	
> 1000 fpm $300' < h \leq 1000'$	"sink rate _____"
> 700 fpm $h \leq 300'$	
<u>Altitude Callouts</u>	
h = 1000' AFE	"1000 feet"
= 500' AFE	" 500 feet"
= DH + 100'	"approaching minimums"
= DH	" minimums"

Table 2.8: Summary of Checklist Items Presented in Time Line Analysis

Phase	Altitude Range	Item	Challenge By	Response By
Descent	18000-10000	1. Fuel Panel "set"	---	S/O
		Hydraulic System B Pump #1 "ON"	---	S/O
		2. Pressurization "SET"	---	S/O
		3. Pack Cooling Doors "OPEN"	---	S/O
		4. Shoulder Harness "ON"	S/O	C, F/O
		5. Landing Data Card "COMPUTED"	---	S/O
		6. CSD Temp. Switches "IN"	---	S/O
Initial Approach	3500-OM	1. Continuous Ignition "ON"	S/O	F/O
		2. Seat Belt "ON"	S/O	F/O
		3. Alt., Flt. & Nav. Insts. "SET/CROSSCHECK"	S/O	C, F/O, S/O
		4. RA/Baro Alt. Bugs "SET"	S/O	C, F/O, S/O
		5. Airspeed & EPR Bugs "SET/CROSSCHECK"	S/O	C, F/O
Final Approach	OM-TD	1. No Smoking "ON"	S/O	C
		2. Landing Gear "DOWN, IN, 3 GREEN LIGHTS"	S/O	C
		3. Flaps "30°, GREEN LIGHT"	S/O	F/O
		4. Anti-skid "CHECK"	---	S/O
		5. Hyd. Pressure & Quantities "CHECK"	---	S/O

It is important to note that, in contrast to flight management and callout tasks which can be located fairly precisely on the chart with respect to objective states of the aircraft, checklist tasks can be located only approximately with respect to mission time. This results from the fact that their execution under real operating conditions varies with such factors as flight time and profile, cockpit tempo and workload, and crew characteristics. Our time-line depicts three characteristically different conditions of checklist execution which can occur: (1) a "late" start and normal execution of the Descent checklist; (2) a "normal" execution of the Initial Approach checklist with interruption for heading, altitude and throttle changes; and (3) an early start and "normal" execution of the Final Approach checklist.

The time-line analysis considered crew activity under both a standard approach procedure (SAP) and a monitored approach procedure (MAP), and the following two subsections discuss these in more detail. A third subsection following details the missed approach procedure, applicable to either SAP or MAP time-lines.

In our presentation of "events" on the time line, we have attempted to maintain a certain rigor in the vocabulary used for describing individual and crew tasks and sub-tasks. A summary of the terms in this vocabulary and of intended meanings is presented in Table 2.9.

Table 2.9: Summary of Procedural Terms Used in Timeline

Term	Meaning	Example
Acknowledge	Notify ATC of receipt of information/ instructions	"Acknowledge" ATC
Adjust	Alter position of control to satisfy criterion	SB Lever "Adjust"*
Announce	Verbal indication of guidance system/ vehicle state or milestone	DH "Announce"
Begin	Initiate change in heading	Turn to HC "Begin"
Check	Verbal confirmation of desired condition; usually combined with term "set"	Flaps "Set," "Check"
Complete	Terminate checklist procedure	Final Approach Checklist "Complete"
Compute	Perform table-look-up/arithmetic operations	Landing Data Card "Compute"
Confirm	Verify required instrument/control/position indication	LOM altitude "Confirm"
Crosscheck	Verify correspondence between instruments	Altimeters "Crosscheck"
End	Terminate change in heading	Turn "End"
IN	Used to indicate active device Synonymous with ON	"Down, In, 3 Green"
Monitor	Scan instruments for out-of-tolerance conditions	Hydraulics, Brakes "Monitor"

Table 2.9 (cont): Summary of Procedural Terms Used in Timeline

Term	Meaning	Example
OFF	Used to indicate an inactive device; Synonymous with OUT	Gear and Door Lights "OFF"
ON	Used to indicate an active device; Synonymous with IN	Shoulder Harness "ON"
Request	Command execution of procedure or satisfaction of a condition	Flaps 25 "Request"
Set	Position a control/bug at a desired value	Flaps 30 "Set"
Start	Initiate checklist procedure	Final Approach Checklist "Start"
Trim	Alter configuration to achieve desired sink rate	Altitude "Trim"

*NOTE: Speed Brake (SB) adjustment is not required on all versions of the 727.

2.2.1 Standard Approach Time-Line

A standard approach procedure was defined in accordance with procedures used by U.S. carriers during CAT I approaches. The SAP was defined so as to include the following procedural elements, in addition to those detailed earlier:

1. No transfer of vehicle control is made, so that one pilot is always the PF, the other always the PNF.

2. Both pilots are "head-down" on instruments, no later than the outer marker.

3. The PNF begins to search for external visual cues, at no later than a specified "search height" (SH), while continuing to monitor the instruments.

4. If, before the decision height (DH), the PNF acquires an adequate view of the runway, and determines that a normal approach to landing can be made solely on the basis of the external visual cues, the PNF announces "runway in sight," and returns to instrument monitoring. If the PNF acquires an adequate view of the runway, but decides that a normal approach to landing cannot be made (either because of vehicle positioning or anticipated deterioration of the visual environment), the PNF announces "missed approach," and returns to instrument monitoring.

5. If the PF hears "runway in sight," the PF directs his attention to the external visual cues and continues the approach. If the PF hears "missed approach," the PF initiates the missed approach procedure. If the PF has heard neither of these announcements by the DH, the PF announces "missed approach" and initiates the missed approach procedure.

6. If the PF has switched his attention to the external visual cues, and determines that a normal approach to landing cannot be made (because of vehicle positioning or visual cue inadequacy), the PF announces "missed approach," and initiates the missed approach procedure.

The standard approach time-line is shown in Table 2.10, and is arranged in columns, with time-to-go (to touchdown) running vertically down the page. The left-hand columns show time-to-go (TGO), ground range-to-go in the localizer plane (R), altitude (A), velocity (V), and heading (H). Units are those identified in Table 2.5. The middle columns show procedural activity by each crew member (Captain, First Officer, and Second Officer); it is assumed here that the Captain is the PF, and the First Officer, the PNF. The last column shows significant event occurrences, and identifies ATIS and ATC communications.

This last column also identifies what might be labelled as "triggering events" which lead to a specific crew action in response to the event. As an example, the time-line shows a flaps 15 request by the PF at t_{go} = 955 sec; the corresponding triggering event is shown in the right hand column: the vehicle velocity reaching 170 kts (V = 170), after having undergone a deceleration from 190 kts. Responses triggered by ATC requests are similarly shown. For example, at t_{go} = 500 sec, the PF initiates a turn to a 270 deg heading, an action triggered by the ATC heading request shown in the right-hand column. In this case, the parentheses indicate that the actual request was made earlier, at t_{go} = 1010 sec.

TGO/R	A/V/H	Captain (PF)	First Officer (PNF)	Second Officer (SO)	Markers, ATIS, ATC, A/V/H milestones
Initial Conditions:		Baro Altimeter "Set, Crosscheck" at 18,000	Baro. Altimeter "Set, Crosscheck" at 18,000		
		Altitude Alert "Set" to 10,000			
******DESCENT******					
1500/	10000/190/210	Altitude Alert "OFF"			A=10000
		Descent Checklist "Request"			
				Descent Checklist "Start"	
				D1. Shoulder Harness?	
		D1. Shoulder Harness "ON"			
			D1. Shoulder Harness "ON"		
		Inboard Landing Lights "ON"			
				D2. Fuel Panel "Set" 1. All main tank fuel boost switches "ON" 2. All crossfeed valve selectors "Set" in accord with Fuel management Procedures	
				D3. Hydraulic Systems "Check" 1. Hy. Sys B pump #1 switches "ON" 2. All pressures (incl. brakes) and quantities normal 3. All low pressure lights "OFF"	
				D4. Pressurization "Set" 1. Cabin Altitudes set to 200' below AE 2. All pressures (incl. brakes) and quantities normal	
				D5. Pack Cooling Doors Open	

Table 2.10: Standard Approach Time-Line

				D7. Landing Data Card "Compute" and "Pass" to Captain 1. Transcribe ATIS I.D., wind, temp., baro., and RWY selected 2. Compute GWT and VREF (130) 3. Compute VBUG (134) 4. Transcribe G/A EPR's D8. "Set" CSD Temp Switches "In" Descent Checklist "Complete"	
		Landing Data "Check, Set" 1. Set VBUG (134) 2. Set EPR bugs to G/A 3. Set other Airspeed as desired			
		Cabin Announcements and Company Communications A/R	Cabin Announcements and Company Communications A/R	Cabin Announcements and Company Communications A/R	
		Final Briefing "Start" 1. Runway to be taken 2. Type of approach 3. MAP course			ATIS: 1. RVR 2. Turbulence 3. Wind Speed 4. Wind Direction 5. Alt. Setting
		Final Briefing "Complete"			
				Fuel Heat "Adjust" A/R	
1010/	10000/190/210	Continuous Ignition "ON"			ATC: HC=270 VC=170 AC=3500
			"Acknowledge" ATC		

		"Set" Altitude Alert to 3500'			
1000/	10000/190/210	Turn to HC "Begin" 3 deg/sec turn rate			(HC=270)
970/	10000/190/270	Turn "End" Maintain 270 deg			H=270
		Throttle "Adjust" Adjust to make VC			(VC=170)
955/	10000/170/270	Flaps 15 "Request"			V=170
			Flaps "Set, Check" 1. Observe flap placard speeds 2. Move flap handle (to 15 deg) 3. Check light indications against flap handle setting		
950/	10000/170/270	Throttle "Adjust" Set to flight idle			(AC=3500)
		Altitude "Trim" Trim for 1800 fpm sink rate	"Announce"..."Out of 10000 for 3500"		

******INITIAL APPROACH**

		Initial Approach Checklist "Request"			
730/	3500/170/270	Altitude Alert "OFF"			A=3500
		Throttle "Adjust" Set for level flight		Initial Approach Checklist "Start"	
				I1. Continuous Ignition?	
695/	3500/170/270				ATC: VC=160
			"Acknowledge" ATC		
			I1. Continuous Ignition "ON"		

				12. Seat Belt?	
690/	3500/170/270	Throttle "Adjust" Adjust to make VC			(VC=160)
			12. Seat Belt "ON"		
680/	3500/160/270	Throttle "Adjust" Set for level flight			
				13. Alt., Flight and Nav Instruments?	
					ATC: HC=180 AC=2000 HC=120@A=2000
			"Acknowledge" ATC		
570/	3500/160/270		13. Alt., Flt. and Nav Instruments "Set, Crosscheck" 1. Check for warning flags 2. Check for instrument agreement 3. Check RF 4. Confirm VOR/ADF selectors/switches for proper position 5. Confirm OM & MM switch positions		
		"Set" Altitude Alert to 2000'			
563/	3500/160/270	Turn to HC "Begin" 3 deg/sec turn rate			(HC=180)
523/	3500/160/180	Turn "End" Maintain 180 deg			
		Throttle "Adjust" Set to flight idle			(AC=2000)
		Altitude "Trim" Trim for 900 fpm sink rate			ATC: HC-90@LOC
		"Acknowledge" ATC			

		"Set" Altitude Alert			
473/	2000/160/180	Altitude Alert "OFF"			A=2000
		Throttle "Adjust" Set for level flight		14. RA/Baro Alt. Bugs?	
		Turn to HC "Begin" 3 deg/sec turn rate			(HC=120@A=2000)
443/	2000/160/120	Turn "End" Maintain 120 deg			H=120
		GPWS switch "Check" verify NORMAL setting	14. RA/Baro Alt. Bugs "Set"		

******FINAL APPROACH**

393/	2000/160/120		"Announce"... "Localizer Capture"		LOC active (HC=90@LOC)
		Turn to HC "Begin" 0.5 deg/sec turn rate			
332/80810	2000/160/ 90	Turn "End" Maintain 90 deg			on LOC
				15. Airspeed & EPR Bugs	
		SB Lever "Adjust" Turn SBL Down	15. Airspeed & EPR Bugs, "Set, Crosscheck"		
				Initial Approach Checklist "Complete"	
			Altitude Alert "Set" Set to 4500		

271.9/68780	2000/160/ 90	Throttle "Adjust" Adjust to 150 kts	"Announce"..."Glideslope Alive"		GS active
262.3/62300	2000/150/ 90	Flaps 25 "Request" Throttle "Adjust" Set for level flight	Flaps "Set, Check" 1. Observe flap placard speeds 2. Move flap handle (to 25 deg) 3. Check light indications against flap handle setting		V=150
218.7/59800	2000/150/ 90	Gear Down "Request" "Trim" to intercept GS	Gear Down "Set, Check" 1. Lower Gear 2. Confirm gear down (green lights "ON") 3. Confirm red Gear and Doors lights "OFF"	Hydraulics, Brakes "Monitor"	1/2 dot below GS
		SB Lever "Arm" 1. Set lever to "arm" 2. Confirm "armed" light "on"	SB "Confirm" Confirm "armed" light "on"		
		No Smoking Signs "ON" Antiskid "ON"			

		Final Approach Checklist "Request"			
				Final Approach Checklist "Start"	
				F1. No Smoking?	
			F1. No Smoking "ON"		
				F2. Landing Gear?	
		F2. Down In, 3 Green			
162.2/33000	1630/150/ 30	Throttle "Adjust" Adjust to make landing flap speed @ GS			
159.0/36680	1550/180/ 30	Landing Flaps "Request" (30 deg)			on GS
			Flaps "Set, Check" 1. Observe flap placard speeds 2. Move flap handle (to 30 deg) 3. Check light indications against flap handle setting	Approach Destabilization "Monitor" Monitor RF, instruments, hydraulic pressure, etc.	
		Throttle "Adjust" Adjust to VAPP (132 kts)		F3. Flaps?	
			F3. Flaps 30, Green Light		
				F4. Antiskid "Check" F5. Hydraulic Pressure and Quantities Normal? "Check" F6. Tail Skid Extension "Check"	
			F6. Tail Skid light "OFF"		

				Final Approach Checklist "Complete"	
149.0/34290	1450/139/ 90	LOM fix "Announce" "Set" Altitude Alert to MAP alt.		LOM alt. "Confirm" (LOM alt.=1450 ft.)	LOM
104.4/24040	1000/139/ 90		1000' "Announce" Instruments Crosscheck		1000' AFE
		DH "Announce" (200')			
			DH "Confirm" (200')		
54.9/12590	500/139/ 90		500' "Announce" Instruments Crosscheck		500' AFE
			500' "Announce" Approach Stability "Monitor" 1. Announce any indications of approach destabilization (sink rate, power changes, sink rate variations) 2. Announce LOC, GS deviations	Approach Stability "Monitor"	500' AFE

35.1/ 8010	300/139/ 90		Approaching Minimums "Announce"		DH+100' (SH)
				Approaching Minimums "Confirm"	
30.2/ 6860	250/139/ 90		Runway-in-Sight "Announce"		250' AFE
27.7/ 6290	225/139/ 90				MM
25.2/ 5720	200/139/ 90		Minimums "Announce"		
15.3/ 3830	100/139/ 90	Throttle "Adjust" Adjust to VBUG (138)			100' AFE
10.3/ 2290	50/138/ 90	Throttle "Adjust" Flare to touchdown			RW Threshold
0/0	0/138/ 90				TD

Checklist items are identified by a letter code to indicate Descent (D), Initial Approach (I), or Final Approach (F). In addition, items within a checklist are numbered according to the sequence of their execution, and items requiring crew interaction are tagged by corresponding letter-number pairs. This tagging thus provides a linkage between checklist queries by one crew member and corresponding responses by one or both of the other crew members.

The time-line presumes that the vehicle "breaks out" at 250 ft AFE, and that, from this point on, the visual cues are adequate to continue the approach and to land the vehicle. It is also assumed that the PNF begins his search for runway cues at a search height 100 ft above DH, acquires those cues at the breakout altitude, and makes the appropriate runway-in-sight call. Although not shown on the time-line, it is also assumed that, at this point, the PNF returns to instrument monitoring, while the PF transitions to the external runway cues, and lands the vehicle.

2.2.2 Monitored Approach Time-Line

A monitored approach procedure was defined in accordance with procedures used by some U.S. carriers during CAT II approaches. The MAP was defined to have most of the procedural elements of the above-described SAP. The exceptions are the SAP procedures given in the preceding subsection; the following MAP procedural elements are defined to replace them:

1. A potential exists for transfer of vehicle control, so that PF and PNF roles can change. For ease of discussion, we assume here that the captain (CAPT) is initially the PNF, and the first officer (F/O) is initially the PF.

2. Both pilots are "head-down" on instruments, no later than the outer marker.

3. The CAPT (PNF) begins to search for external visual cues, at no later than a specified "search height" (SH), while continuing to monitor instruments.

4. If, before the DH, the CAPT (PNF) acquires an adequate view of the runway, and determines that a normal approach to landing can be made solely on the basis of external visual cues, the CAPT (PNF) announces "taking control," takes over vehicle control, and continues the approach (as the PF). If the CAPT (PNF) acquires an adequate view of the runway, but decides that a normal approach to landing cannot be made (either because of vehicle positioning or anticipated deterioration of the visual environment), the CAPT (PNF) announces "missed approach," and returns to instrument monitoring.

5. If the F/O (PF) hears "taking control," the F/O (PF) relinquishes vehicle control, and continues to monitor the instruments (as the PNF). If the F/O (PF) hears "missed approach," the F/O (PF) initiates the missed approach procedure. If the F/O (PF) has heard neither of these announcements by the DH, the F/O (PF) announces "missed approach," and initiates the missed approach procedure.

Since the MAP differs from the SAP only in the last few hundred feet of the approach, we show the MAP time-line, in Table 2.11, to start from the SH and proceeding to TD. The MAP time-line for events prior to this time would be identical to that shown for the SAP in Table 2.10, with the flying duties of the Captain and First Officer reversed (i.e., CAPT is PNF and F/O is PF).

TGO/R	A/V/H	Captain	First Officer	Second Officer (SO)	Markers, ATIS, ATC, A/V/H milestones
35.1/ 8010	300/139/ 90	Approaching Minimums "Announce"			DH+100' (SH)
				Approaching Minimums "Verify"	
30.2/ 6860	250/139/ 90	Runway-in-Sight "Announce"			250' AFE
27.7/ 6230	225/139/ 90	Control "Takeover"	Control "Relinquish"		MM
25.2/ 5720	200/139/ 90		Minimums "Announce"		DH
15.3/ 3430	100/139/ 90	Throttle "Adjust" Adjust to VBUG (138)			100' AFE
10.3/ 2230	50/138/ 90	Throttle "Adjust" Flare to touchdown			RW Threshold
0/0	0/138/ 90				TD

Table 2.11: Monitored Approach Time-Line

As with the SAP time-line, a "break out" altitude of 250 ft AFE is presumed. It is also assumed here that the CAPT (PNF) begins his search for runway cues at a search height 100 ft above DH, and acquires those cues at the breakout altitude. After making the appropriate takeover call, the CAPT takes control of the vehicle from the F/O, who remains on instruments to monitor the CAPT's approach progress.

2.2.3 Missed Approach Procedure

Since neither of the above time-lines required the execution of a missed approach, the associated procedure is not called out. The procedure is detailed, however, in Table 2.12, which shows the specific control actions involved in the procedure, and the predicating conditions for their execution. The first condition is simply an affirmative decision to execute the overall procedure. The affirmative decision is followed by an immediate application of power and a change in pitch to 10 deg nose-up by the PF. These actions are followed by a request to the PNF for retraction of flaps to 25 deg. When a positive rate of climb has been established, PF requests gear retraction by PNF, and later, at an airspeed of (VBUG + 10), a retraction of flaps to 15 deg. In the event that airspeed reaches (VBUG + 10) before a positive rate of climb is attained, the latter two steps are performed in the reverse order.

Table 2.12: Missed Approach Procedure

Condition	Action
1. decide to execute missed approach	i) apply "go-around" thrust* ii) pitch up to 10 deg nose-up attitude iii) retract flaps to 25 deg
2. attain positive climb rate	retract gear
3. attain airspeed of (VBUG + 10)	retract flaps to 15 deg

* according to landing data card EPR values

During execution of a missed approach, it is assumed that all actions concerned with thrust and attitude management are made directly by the PF and that all actions concerned with control surfaces and gear are made by the PNF on request by the PF.

The decision to execute a missed approach is less well-defined than the procedure itself. However, a set of general conditions can be specified for defining when the procedure should be executed, and these are:

1. Vehicle altitude is less than FH ft AFE, and a failure is noted in either a flight instrument or an ILS instrument component.
2. The vehicle is within the OM, but not stabilized on the glide slope.
3. An adequate view of the runway is acquired before DH, but a normal visual approach-to-landing cannot be made, either because of vehicle positioning with respect to the runway, or because of anticipated deterioration of the visual environment.
4. An adequate view of the runway is not acquired by the time the vehicle reaches DH.

The first item above leaves unspecified the "failure height" ceiling (FH), but it would appear that 500 ft AFE would be a reasonable value. Instrument failures relating to this condition would be either "hard" failures, where the nature of the failure is obvious, or "soft" failures, such as might be associated with an instrument disagreement between crew members.

The second item presumes that stabilization requires the vehicle to be within a specified approach "window," defined along specific position, velocity, and attitude coordinates. The position window is defined in terms of localizer deviation, glide slope deviation, and altitude deviation (from a given nominal range-dependent altitude); the velocity window in terms of deviations from the nominal approach speed and sink rate; and the attitude window in terms of roll, pitch, and yaw deviations from nominal trim values. Implicit in this window definition is that the rates-of-change of these variables are also within specified limits, to ensure stabilization throughout the entire course of the approach.

The third item requires that two conditions be met for continuing the approach. First, the runway view must be clear and detailed to an extent which would allow for an approach and landing utilizing only out-the-window cues. This implies that possible future deterioration of the visual environment must be considered, since a later loss of out-the-window cues would preclude a visual landing. Given an adequate visual environment, a second requirement is that the vehicle be within an approach window which is sufficiently small to allow for a normal approach and landing. As in the previous item, a multi-dimensional window is presumed, with sufficiently narrow tolerances to ensure sufficiently accurate touchdown footprints with a minimum of vehicle maneuvering.

The final item precludes a continued approach below DH, without the prior acquisition of an adequate out-the-window cue set. It presumes that no further attempt will be made to acquire the runway environment, and that a missed approach will be executed in a timely manner.

3. PROCRU: A MODEL FOR ANALYZING FLIGHT CREW PROCEDURES

The task that has just been described involves a wide range of human behaviors and activities, both cognitive and perceptual-motor. These include monitoring and information-processing, flight control, decision-making, execution of standard procedures, and communication with other crew members and with ATC. The goal here was to develop a model for this complicated process that would provide a means for systematic exploration of questions concerning the impact of procedural and equipment design and the allocation of resources in the cockpit on performance and safety in approach-to-landing.

Given the objectives we have for the model and the nature of the issues we hope to analyze with it, several general implications for modelling the task emerge. First, it is clear that a system model is needed; one that accounts for the interactions of crew, procedures, vehicle, approach geometry, and environment. Second, the issues of interest revolve principally around allocation of tasks in the cockpit and crew performance with respect to the cognitive aspects of the tasks. The model must, therefore, deal effectively with information processing and decision-making aspects of human performance. Third, despite the high cognitive content of the approach task, a large portion of the crew's activities involves highly structured, standard procedures. These must be

modelled at a level that is adequate for determining how performance on these tasks interferes with other tasks (and vice-versa) and for evaluating the consequences of failure to execute important procedures. Fourth, communication among crew members and between the crew and ATC must be considered in the model, at least with respect to accounting for the transfer of information and the load imposed by such communication. Finally, to examine the impact of various system conditions and assumptions, it must be possible to compute performance parameters of interest. Moreover, for analysis purposes, it will be very useful to maintain an estimate of the information possessed by each member of the crew at each instant in time. This will allow evaluation of the information upon which decisions are made in the model. In addition, it may provide an implicit performance metric (not measurable in a simulation) for evaluating various approach procedures.

PROCRU (Procedure Oriented Crew Model), is a simulation model for examining crew procedures in approach to landing, developed with the above requirements in mind. It includes a system model and a model for each crew member. The crew is assumed to be composed of three members: pilot flying (PF), pilot not flying (PNF) and second officer (SO). In the present implementation of PROCRU, the SO model does not include any information processing or

decision-making components. Rather, the SO is modelled by a purely deterministic program that responds to events and generates requests. PF and PNF, on the other hand, are each represented by complex human operator models which have the same general form but differ in detail. The basic structure of the PROCRU model for PF or PNF is illustrated in Figure 3.1. In the remainder of this chapter we describe the elements in that structure.

3.1 System Model

3.1.1 Vehicle Dynamics

The representation of vehicle dynamics must be sufficient to capture the essential aspects of the task but there is an incentive (computational cost) to keep it as simple as possible. Certainly, the equations of motion must be adequate to describe the position and velocity of the aircraft relative to the nominal approach path, but for the issues to be addressed here linearized equations can be used and inner-loop (high-frequency) dynamics ignored, to a first approximation. Thus, we use as a basis for the dynamic calculations the following standard point mass equations for the vehicle trajectory:

$$\begin{aligned} m\dot{V} &= T\cos\alpha - mg\sin\gamma - D(\alpha) \\ (mV\cos\gamma)\dot{\psi} &= (L(\alpha) + T\sin\alpha)\sin\phi \\ mV\dot{\gamma} &= (L(\alpha) + T\sin\alpha)\cos\phi - mg\cos\gamma \end{aligned} \tag{3.1}$$

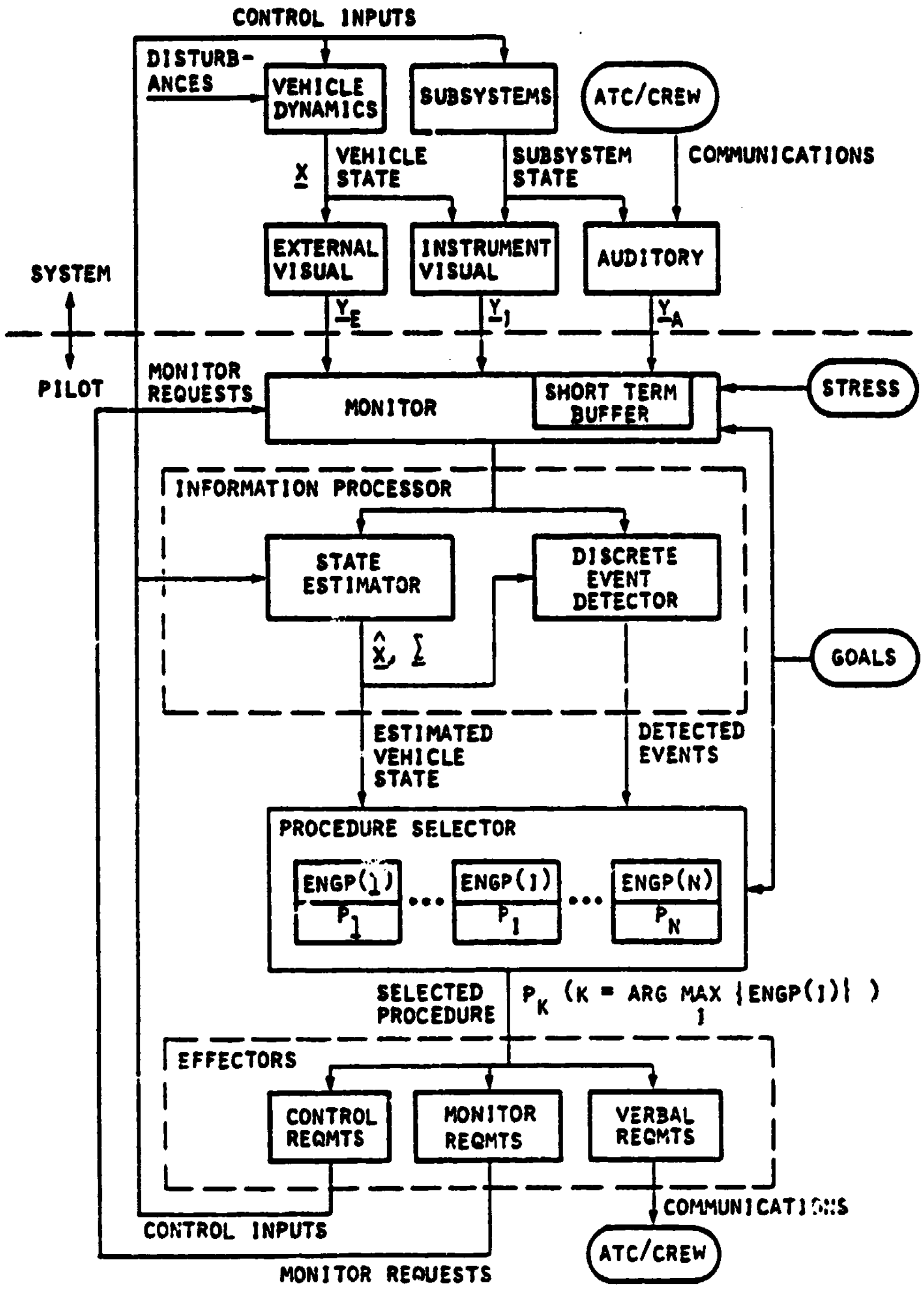

Figure 3.1: Model Structure for Crew Member Analysis

$$\dot{h} = V\sin\gamma$$

$$\dot{x} = V\cos\gamma\cos\psi$$

$$\dot{y} = V\cos\gamma\sin\psi$$

where the variables are defined as

V: velocity

ψ: heading

γ: flight path angle

x: distance north from the glide slope transmitter

y: distance east from the glide slope transmitter

h: altitude above the runway (assumed to be at zero elevation).

L: Lift (function of angle of attack)

D: Drag (function of angle of attack)

α: angle of attack

ϕ: bank angle

T: Thrust

These equations may be written in the general form

$$\dot{\underline{X}} = \underline{f}\,(\underline{X},\underline{U},t) \tag{3.2}$$

where $\underline{X} = (V,\psi,\gamma,h,x,y)$ is the vehicle state vector and $\underline{U} = (T,\phi,\alpha)$ is the control input.

The scheme utilized to "integrate" the above equations and to provide the linearized equations needed for implementing the control and estimation portions of PROCRU is somewhat novel and, we believe, is in keeping with the manner in which approach trajectories are flown. It is described in detail, specifically for Eqn. (3.1), in Appendix C. Briefly, five "nominal trajectory" segments, corresponding to five standard maneuvers, are defined:

1) straight and level flight ("S & L")
2) deceleration at constant flight path angle and heading ("DECEL")
3) turn at constant rate, airspeed and altitude ("TURN")
4) flare constant rate of change of flight path angle at constant speed and heading ("FLARE")
5) descend at constant sink-rate, airspeed and heading ("DSCNT")

It is possible to determine, algebraically, for each maneuver, the "trim" or "nominal" controls $\underline{U}_N$, necessary to achieve the desired condition and, moreover, to integrate the corresponding equations of motion exactly to obtain $\underline{X}_N(t)$ (See Appendix C). The equations can then be linearized about the particular segment to yield equations of the form

$$\dot{\underline{x}} = \underline{A}_{N_i}\underline{x} + \underline{B}_{N_i}\,\underline{u} \tag{3.3}$$

where

$$\underline{X}(t) = \underline{X}_{N_i}(t) + \underline{x}(t)$$

$$\underline{U}(t) = \underline{U}_{N_i}(t) + \underline{u}(t) \tag{3.4}$$

$$A_{N_i} = \left.\frac{\partial f}{\partial X}\right|_{N_i}, \quad B_{N_i} = \left.\frac{f}{U}\right|_{N_i}$$

and the subscript N_i means that the quantity is evaluated along the i'th nominal segment.

We note that it is not necessary for a nominal segment to start at a particular place (see discussion of procedures below). In addition, because the system matrices change from segment to segment (and from moment to moment in a TURN segment), the linearized equations (3.3) will be time-varying (piecewise constant) over the approach trajectory. Finally, we may generalize Eqn. (3.2) to include wind and other possible disturbances by rewriting it as

$$\dot{\underline{x}} = \underline{A}_{N_i}\, \underline{x} + \underline{B}_{N_i}\underline{u} + \underline{E}_{N_i}\, \underline{w}_{N_i} + \underline{F}_{N_i}\underline{z}_{N_i} \tag{3.5}$$

where W_{N_i} is a zero-mean white noise with covariance $\underline{W}_{N_i}$ and $\underline{z}_{N_i}$ is a deterministic disturbance that is unknown to the pilot. Eqn. 3.5 is in a form that is standard for applying the Optimal Control Model (OCM) of the human operator [2].

3.1.2 Subsystems

Aircraft subsystems, such as engines, hydraulics, etc., are not modelled in any detail. Subsystem operation, when required by

procedures, is accomplished, or not, as determined by the models for the crew. (See discussion of procedures and displays).

3.1.3 ATC Communications

Air Traffic control vectoring commands are preprogrammed as part of the approach scenario. They take the form of auditory guidance commands, to be processed and executed by the PF.

3.1.4 Instrument Landing System

The instrument landing system model includes the glide slope, localizer, outer marker and middle marker. Computed vehicle position is used to compute "activation" of any of these ILS signals and to determine glide slope and localizer errors in "dots" (See Appendix B). ILS transmitter positions are as indicated in Chapter 2. The model does not presently include any beam errors but these could be added without difficulty.

3.1.5 Information Sources

We assume that four basic sources or "clusters" of information are available to a crew member: external visual scene information, visual information concerning vehicle state from the flight instruments, visual information concerning subsystems and auditory information.

The information from the external visual scene depends on the position and attitude of the aircraft relative to the airfield and on the weather. Geometric analysis allows us to define how the "displayed" quantities, $\underline{y}_E$, depend on vehicle state and scene content (see Appendix D). Previous analyses of manually controlled approaches with visual scene information using the OCM have been performed fairly successfully with such a representation [3,4].

The information on the instrument panel, $\underline{y}_I$, can relate to vehicle status information (from flight instrumentation), command information (from flight directors) and subsystem information (including subsystem status and visual "alarms"). The information may be discrete as well as continuous. We assume this information is separated into two clusters, one for vehicle state-related information, $\underline{y}_I$, and one for subsystem information. For the PROCRU analysis conducted herein, the flight displays are assumed to indicate airspeed heading, altitude, rate-of-climb and, after beam intercept, localizer and glide slope error. The subsystem displays are not modelled with respect to information content but serve as an attention distraction or "sink" when a procedure requiring subsystem operation is being performed (see below).

Auditory information includes command information from ATC, auditory alarms, and communications from other crew members such as callouts, requests, etc.

3.2 Human Operator Models

The model for the human operator (PF or PNF) contains submodels for monitoring, information processing, decision-making (procedure selection) and action. These are discussed below.

3.2.1 Monitor

The monitor sub-model accounts for the operator's sensory limitations as well as for monitoring decisions (i.e., allocation of attention). The visual sensory limitations are modelled in the same manner as in the OCM [2,3], except that the perceptual delay is neglected. In particular, an observation noise and a threshold are associated with each observed visual quantity. The thresholds are important for external visual scene perception; for example, in limiting the quality of available vertical guidance information. Thus, if $\underline{y}_E$ and $\underline{y}_I$ correspond to displayed information concerning vehicle state from the external scene or instruments, respectively, then

$$\underline{y}_E(t) = \underline{C}_E\ \underline{x}(t) + \underline{v}_E(t)$$
$$\underline{y}_I(t) = \underline{C}_I\ \underline{x}(t) + \underline{v}_I(t) \quad (3.6)$$

where $\underline{v}_E$ and $\underline{v}_I$ are white, zero-mean gaussian noises with the autocorrelation of $\underline{v}_E$ given by

$$E\left\{v_{E_j}(t)v_{E_k}(s)\right\} = V_{E_j}(t)\delta(t-s)\delta_{jk} \qquad (3.7a)$$

where

$$\sum_j f_{E_j}(t) = 1, \quad 0 \leq f_{E_j}(t) \forall \leq 1 \qquad (3.7b)$$

$$N_{E_j} = \text{erfc}\ [|y_{E_j}(t)|/a_j\sqrt{2}] \qquad (3.7c)$$

$$V_{E_j}(t) = V_{E_j}{}^{o} + \frac{P_{E_j}\ E\left\{y_{E_j}{}^{2}(t)\right\}}{f_{E_j}(t)\ N^2_{E_j}(t)} \qquad (3.7d)$$

$$\int_{-\infty}^{\infty} \delta(t-s)ds = 1 \quad t=s,\ 0 \text{ otherwise}$$

$$\delta_{ij} = 1 \quad i=j,\ 0 \text{ otherwise} \qquad (3.7e)$$

The quantity f_E in (3.7a) is the attention devoted to cluster E (i.e., external scene) and f_{E_j} is the attention to the j-th "display" in that cluster. N_{E_j} is the random input describing function for a threshold with value a_j. The base observation noise covariance $V_E(t)$ has a constant component $V_E{}^{o}$ as well as a portion that scales with the signal; P_E is the noise-to-signal ratio. A similar set of expressions holds for the autocorrelation and autocovariance of $\underline{v}_I$.

Auditory information is assumed to be heard correctly. It is stored in a memory buffer for subsequent processing.

The operator cannot process all sources of information simultaneously and must, therefore, decide which sources to "attend to." In the case of visual information there is a fundamental

choice as to where to fixate, on the external world or on the instrument panel. If the instrument panel is chosen, the operator must decide upon which instrument to fixate. We shall also assume that the auditory information similarly "competes" with the visual information for operator attention.

Thus, we let

$$f_E(t) + f_I(t) + f_S(t) + f_A(t) = 1, \forall\, t \tag{3.8}$$

where f_E and f_I are defined above and f_S and f_A are the attentions devoted to subsystem displays and the auditory channels, respectively. The quantity f_S is either one or zero, depending on whether or not a "request" for subsystem information has been made. Similarly, f_A is one if an auditory message is being processed and zero otherwise. Within the flight displays, we follow [5] and assume that attention is shared, and the observation noises modified, as indicated by (3.7a,b). The fractions devoted to individual flight displays at a given time are determined by the particular procedure invoked at that time, in a manner to be described later. For the moment, we simply note that if a crew member is observing the flight instruments and a procedure is activated that issues a "monitoring request" for a given display, then the fraction of attention devoted to that display is incremented to approximately full attention while the fractions

devoted to the remaining displays are decremented correspondingly.

To summarize, when auditory or subsystem information is requested by a procedure, attention is diverted from the flight displays and no information concerning the vehicle's state is obtained (except if it comes via the auditory channel from another crew member). When flight displays are being observed, attention is assumed to be shared among the displays on a continuous basis instead of being restricted to a single display at a time. Employing this "mixed strategy" for flight display scanning appears to us to have considerable theoretical merit in an environment in which randomness is an essential part.

3.2.2 Information Processor

The information processor portion of the model consists of two sub-models, an "estimator" and a "discrete event detector". The estimator is identical to that used in the OCM and is a time-varying Kalman filter. The internal model for the filter changes with changes in dynamics resulting from alteration of the "nominal" or from flap or gear extensions or with changes in disturbance characteristics. In a manual approach, the PF has knowledge of the control inputs; non-flying crew do not have such information.

The outputs of the estimator are the estimate of the perturbed state, $\hat{\underline{x}}$, the covariance of the estimation error, $\underline{\Sigma}$, and, perhaps, the innovations sequence, and its covariance.* We will assume that the probability distribution for $\underline{x}$ is normal, in which case $\hat{\underline{x}}$ and $\underline{\Sigma}$ are sufficient statistics for determining the conditional density of $\underline{x}$ based on past observations $\underline{y}$, $P(x|y)$. Thus, the estimator produces status information, $\hat{\underline{x}}$, needed for control and "subjective" probability estimates that can be used for decision-making or detection. Note that the error covariance, $\underline{\Sigma}$, is a measure of the operator's uncertainty in the estimate $\hat{\underline{x}}$ and will be a major factor in determining monitoring decisions, as will be seen below.

The discrete event detector is intended to model those aspects of operator information processing other than vehicle state estimation. Typically, it is concerned with determining or detecting that an event has occurred which "enables" a subsequent procedure execution. The event may be a failure (that did or did not result in an alarm), a request for action (say from ATC), or some annunciated condition (e.g., crossing OM, glide slope active or, passing through some altitude). The inputs to the event detector are outputs of visual alarms, auditory information, <u>and</u> the outputs of the state estimator. The state information is used to detect state related events such as an unstabilized approach condition.

*In the present implementation of PROCRU, it is assumed that the nominal state $\underline{X}_N(t)$ is known to the crew.

Highly sophisticated models exist for certain types of failure detection based on state estimation, and these might eventually be incorporated in the event detector model (e.g.,[6]). We did not get so sophisticated here, however. We assume, simply, that the occurrence of an event is detected with a specified, finite probability by the crew.* However, the nature of the event is assumed to be unknown until the procedure for decoding messages (see Chapter 4) is invoked. The selection of this procedure can be delayed by the requirements to perform other tasks, thus delaying the effective time of event detection. Once the message associated with the event is decoded, it will generally result in the "enabling" or "triggering" of an appropriate procedural response.

3.2.3 Procedure Selector

The operator is assumed to have a number of procedures or tasks that may be performed at each instant. These "procedures" might be quite general, such as "fly the airplane" or "monitor the approach," or they might be quite specific, such as performing a particular checklist or requesting a specific flap setting; they are described in detail in Chapter 4. Here, we discuss the model for procedure selection.

* The probability is chosen to be one for this study, for simplicity.

We assume that the operator knows what is to be done and, essentially, how to accomplish the objective. However, he must decide what procedure to do next. This is a decision among alternatives and the procedure selected is assumed to be the one with the highest expected gain for execution at that time. The Expected Gain for executing a Procedure, EGP, is a function that is selected to reflect the urgency or priority of that procedure as well as its "value". In addition, the EGP can be a function of the "enabling" state of the procedure. Thus, if a procedure were not "enabled" it would have zero gain and would not be chosen; if the enabling event had a non-zero probability of occurrence, the procedure might then be selected.

In PROCRU, we have assumed the EGP functions have the following general form (specific expressions are given in Section 4.3.3):

$$EGP(I) = G(I) + G_O(I), \quad I=1,\dots,N \tag{3.9}$$

where I denotes the Ith procedure, G(I) is a function that reflects the "situational relevance" of the procedure and $G_O(I)$ is a constant that depends on the relative "value" of the procedure. For procedures that are triggered by the operator's internal assessment of a condition related to the vehicle state-vector, the G(I) functions are appropriate subjective probabilities, based on $\hat{\underline{x}}$

and $\underline{\Sigma}$, as determined by the information processing portion of the model. Procedures that are triggered by events external to the operator, such as ATC commands, communications from the crew, etc., are characterized by G's that are explicit functions of time. For either type of function, the gain for performing a procedure will increase, subsequent to the perception of the triggering event, until the procedure is performed or until a time such that the procedure is assumed to be "missed" or no longer appropriate for execution.

The G_O terms have two principal purposes. First, they are used to establish a "default" procedure for each operator by assigning a base value for EGP for that procedure that is greater than for any other one. (The G(I) for any other procedure must exceed this base value before the procedure can be selected.) For PF the default is flying the airplane, whereas for the PNF it is monitoring the vehicle's status. The second purpose of the G_O term is to establish priorities among procedures that might have the same situational relevance at a given time.

Procedures may be comprised of a number of sub-procedures, so that at the completion of each sub-procedure, a decision to continue must be made. This will permit interruption of such a procedure, depending on the outcome of the decision.

We believe that this model for procedure selection captures many important aspects of human performance in a multi-task environment, and is directly relevant to investigating the efficacy of flight crew procedures. It allows for procedures to be missed and/or interrupted: even flying the airplane may be neglected, as can happen. Although we do not expect sub-procedural steps to be performed out of order with this modelling approach, it would be possible to preprogram such errors if desired.

The output of the procedure selector is a choice of the procedure to perform next; procedure (or sub-procedure) k* is selected according to:

$$k^* = \text{ARG MAX EGP (I)} \tag{3.10}$$

3.2.4 Effectors

The selection and execution of a procedure will result in an action or a sequence of actions. Three types of actions are considered: control actions, monitoring requests and communications. The control actions include continuous manual flight control inputs to the aircraft and discrete control settings (switches, flap settings, etc.). Monitoring requests result from procedural requirements for specific information and, therefore, raise the attention allocated to the particular information source.

We note that verifying that a variable is within limits may not require an actual instrument check, if the operator already has a "confident" internal estimate of that variable. Communications are verbal requests or responses as demanded by a procedure. They include callouts, requests or commands, and communications to ATC.

Associated with each procedural action is a time to complete the required action. (It is possible to modify PROCRU to allow for a probabilistic distribution of action times). When the operator decides to execute a specific procedure, it is assumed that he is "locked in" to the appropriate mode for a specified time. For example, if the procedure requires "checking" a particular instrument and it is assumed that it takes t seconds to accomplish the check, then the "monitor" will not attend to other information for that period, (except for a minimal residual attention), nor will another procedure be executed.

In PROCRU, procedural implementation is modelled as essentially error free. However, errors in execution of procedures can occur because of improper decisions that result from a lack of information (quantity or quality) due to perceptual, procedural and workload limitations. If the effects of action errors are also to be analyzed, this is accomplished by deliberately inserting such errors directly into the model. It should also be pointed out that verbal communication is modelled directly as the transfer of either state, command or event information.

3.3 Summary

In the previous sections, we have described the structure of the PROCRU model for analyzing crew procedures in approach-to-landing. The model employs the information processing structure used in the Optimal Control Model and in recent models for monitoring and failure detection. Mechanisms are added to this basic structure to model crew decision-making in a multi-task environment. Decisions are based on probability assessments and potential mission impact (or gain). Sub-models for procedural activities are also included. Where these procedures affect aircraft responses or the information state of the crew, the effects are accounted for explicitly; where they affect sub-system operation, only the attentional load they impose is considered. Procedures can be interrupted and finished subsequently, or not completed at all, based on decisions made by the model. However, the initial implementation of the model does not permit procedural steps to be skipped over or reordered.

The model distinguishes among external visual, instrument visual, and auditory sources of information. The visual perception models incorporate appropriate limitations for obtaining information. The auditory channel contains a buffer to allow for storage in memory of information until it can be processed. These models of the information sources, along with the monitoring and

information processing models, allow for investigation of issues related to instrument display and external viewing, and to the transfer of information through ATC and crew communication.

A key aspect of the model is the actual definitions of the various procedures incorporated. Those are given in the next chapter.

4. DEFINITIONS OF PROCEDURES

The definition of procedures is an essential step in developing PROCRU. All crew actions, except for the decision as to which procedure to execute, are determined by the procedures. We emphasize that we use the term procedure here to apply to tasks in general; a procedure in these terms could have considerably more cognitive content than might normally be considered to be the case. In this chapter, we describe and define the procedures currently included in PROCRU. An overview is presented first, followed by detailed definitions of procedures, a discussion of the expected gain functions (EGP's) and some comments on procedure execution.

4.1 Procedure Categories and General Overview

Table 4.1 categorizes the approach to landing flight procedures for the PF and PNF. For each crewman, six categories are shown, and for each category, specific types of procedures are itemized. We briefly discuss these categories and types in the following paragraphs.

The vehicle control procedures assigned to the PF are broken down into three types: maneuvering control, regulatory control and retrimming control. The first involves the determination of appropriate maneuver rates, setting trim control values to effect these rates, and monitoring for maneuver termination. In effect,

Table 4.1: PF and PNF Procedures

PF	PNF
1. Vehicle Control Procedures a) Maneuver b) Regulate c) Retrim	1. Vehicle Monitor Procedures a) Vehicle status determination b) Failure detection and identification
2. Request Procedures a) Flap request b) Gear request c) Checklist initiate request	2. Callout Procedures a) Vehicle position callout b) Altitude callout c) Approach stability callout
3. Subsystem Procedures a) Altitude alert monitor/control b) Misc. subsystem monitor/control	3. Subsystem Procedures a) Flap monitor/control b) Gear monitor/control c) Misc. subsystem monitor/control
4. Acknowledgement Procedures a) Checklist item acknowledgement	4. Acknowledgement Procedures a) Checklist item acknowledgement b) ATC request acknowledgement
5. SAP/MAP Terminal Procedures	5. SAP/MAP Terminal Procedures
6. Miscellaneous Procedures a) General message processing b) Landing parameter selection	6. Miscellaneous Procedures a) General message processing

open-loop maneuver control provides us with a means of generating the "nominal" trajectory of Eqn. 3.4. Regulatory control, on the other hand, involves monitoring the display perturbations away from the nominal, estimating the corresponding vehicle state perturbations, and generating an appropriate perturbation control to control out the variations. Closed-loop regulatory control ensures proper execution of the desired maneuver. Finally, retrimming control provides a means of retrimming the vehicle after a flap or gear setting change has altered the vehicle trim conditions.

The vehicle monitoring procedures assigned to the PNF are also broken down into two types: monitoring for vehicle status, and monitoring for event or failure detection. The former involves determining an appropriate monitoring strategy for attention sharing among the available displays, estimating the corresponding vehicle state, and evaluating the approach progress based on the current state estimate. The latter involves a similar process, but is centered on detecting events or failures.

Requests and callouts made by the PF and PNF, respectively, involve verbal responses based on estimates of current vehicle status. The flap, gear, and checklist requests made by the PF involve determining the vehicle's approach progress in terms of one or more trajectory/instrument parameters, and making the request

based on the progress and in accordance with a well-defined set of request procedures. The position and altitude callouts made by the PNF involve a similar process. The approach stability and runway-in-sight (RWIS) callouts, also made by the PNF, involve the additional requirement of determining when the vehicle is in an appropriate "window" for making or not making the callout.

Subsystem monitoring and control actions made by both pilots are assumed to be event driven, and involve discrete control actions and/or diversion of attention from flight displays for appropriate subsystem servicing. For the PF, servicing the altitude alert subsystem is distinguished from the servicing of all other subsystems, because of the interactive nature of setting the trigger point, responding to the alarm, and resetting it. For the PNF, the flap and gear subsystems are called out because of their impact on approach progress, their unique status of being driven by requests from the PF, and because of the need for subprocedures involving validation of the request, and setting and checking of the subsystem involved.

Verbal acknowledgements made by the PF and PNF are driven by checklist item prompts generated by the SO. These require the checking of an appropriate subsystem (attention-diversion) and making the appropriate verbal response. The PNF is also assigned the duty of acknowledging the receipt of ATC vector requests.

The SAP/MAP terminal procedures provide for appropriate callouts, head-up/head-down switching strategies, and missed approach initiation during the terminal phase of either the Standard Approach Procedure (SAP) or the Monitored Approach (MAP). Although this category of procedures could be allocated item by item to the other categories, it has been found to be more convenient to treat it as a uniform procedural category, both for the purpose of modelling, and for discussion.

The miscellaneous procedures shown are primarily for the purpose of modelling convenience, and are not intended to directly represent "by-the-book" or actual procedures engaged in by the crew. They include processing and decoding of verbal communications, auditory alarms, and discrete visual events. In addition, for the PF, they involve selection of appropriate landing configuration parameters.

4.2 Detailed Procedure Descriptions

In the following subsections, we present additional detail concerning the structure and function of the procedures just outlined. As is evident from Table 4.1, there is a natural correspondence between many of the procedures assigned to the PF and PNF; as a consequence, the discussion below will be organized along procedural lines, rather than split between the two crewmen.

Before proceeding, however, it should be noted that some of the procedures described here differ slightly from some of those outlined earlier in Chapter 2. The differences are due to subsequent discussions with flight crew members, additional research with current operations flight manuals, and a need for semantic formalization imposed by the model programming effort. As will be seen in Chapter 5, these changes have little impact on the overall approach progress and crew activity time-line already presented in Chapter 2.

4.2.1 Maneuver Procedure

This procedure is assigned to the PF, and has as its basic objective the open-loop control of the vehicle's flight path. The sequence of functions which are required to implement this procedure is outlined in Table 4.2.

The first step involves defining the maneuver: defining which vehicle state variable is to be changed (x), what value is to be reached by the end of the maneuver (x_{cmd}), and at what rate the maneuver is to be carried out* ($\dot{x}_{cmd}$). The procedural rules for choosing these values are maneuver dependent, and we will discuss them shortly. Once the maneuver has been defined, the second step

* This last item presupposes a constant rate maneuver, an assumption which was utilized in Appendix C, in the derivation of the nominal and perturbation equations of motion.

Table 4.2: Maneuver Procedure - Functional Sequence for PF

Step	Action
1	Define stopping condition, maneuver rate ($x_{cmd}, \dot{x}_{cmd}$)
2	Solve for trim controls (T_c, α_c, ϕ_c,)
3	Define appropriate regulatory weightings ($v_{max}, \gamma_{max}, \ldots$)
4	Set trim controls
5	Monitor for stopping condition satisfaction
6	Process next maneuver (go to step 1)

involves a solution for the trim controls (T_c, α_c, ϕ_c) needed to effect that maneuver. We will not detail that solution procedure here, but instead refer the reader to section C.7 of Appendix C, which outlines the basis of an appropriate algorithm.

The third step requires a definition of the appropriate weightings to be used, for regulating out perturbations about the upcoming maneuver trajectory. A discussion of the choice of these weightings is deferred to section 4.2.2, where we discuss regulation control procedures.

Once the maneuver parameters have been set, the fourth step provides for an actual setting of the three controls to their desired trim settings. Once this has been done, the PF is assumed to transition to the regulatory control procedure, to ensure that the desired maneuver is followed.

As the maneuver progresses, there is a requirement on the part of the PF to ensure that the maneuver is stopped at the appropriate point. The fifth item provides for this capability by requiring appropriate monitoring, estimation, and decision-making to identify when the end condition (x_{cmd}) has been reached.

Once it has been determined that the maneuver has been completed, the PF faces one of two options: either continue along the flight path set up by the completed maneuver, or initiate another maneuver. The last step shown in Table 4.2 provides for those options by assuming that another maneuver will always be initiated, either of the type which requires a change in the current flight path (a maneuver in the traditional sense) or of a "default" type which ensures the continuance of the current flight path.*

* If a maneuver ends with a deviation from a commanded value of velocity or angle, this deviation is treated as a perturbation or error to be "regulated out" during the subsequent maneuver.

The "default" maneuver is defined by requiring that velocity, heading and flight path angle be held at the values achieved at the end of the last maneuver. Naturally, if the last maneuver involved a change in one of these states, executing the default maneuver will, at the least, require a change in the trim control settings. Thus, in generic form, the default maneuver has procedural requirements no different from any other. Table 4.2 thus provides for exactly the same procedural steps, except that step 5 is bypassed, since no explicit stopping condition is specified for the default.

We now define the procedural rules for executing step 1 of Table 4.2, and discuss them according to maneuver type.

Velocity Maneuvers

Table 4.3 summarizes the velocity maneuver procedures considered here, in terms of the "triggering" condition for executing a particular maneuver, the associated maneuver command, and the desired maneuver rate.

The first entry indicates that velocity maneuvers will be initiated in response to ATC speed management requests. The commanded velocity is simply that requested by ATC; the maneuver rate is assumed fixed at ± 1 kt/sec, depending on whether an acceleration or deceleration is requested.

Table 4.3: Velocity Maneuver Procedures

	TRIGGER CONDITION	COMMAND	RATE COMMAND
1.	ATC ACCEL/DECEL REQUEST	$v_{cmd}=v_{ATC}$	$\dot{v}_{cmd}=\pm$ 1 kt/sec
2.	CFL & LOC ACTIVE	=150 kt	=-1 kt/sec
3.	$\varepsilon_{GS}=-1.5$ dot	=140 kt	=-1 kt/sec
4.	$\varepsilon_{GS}=-1.0$ dot	$=v_{app}$	=-1 kt/sec
5.	h = 150 ft	$=v_{thresh}$	=-0.5 kt/sec

The remaining entries correspond to flight manual speed management procedures. The first deceleration to 150 kt is triggered by two events: localizer activity and a cleared for landing message (CFL) from ATC. The remaining decelerations are state/display dependent. The approach and threshold speeds, v_{app} and v_{thresh}, are assumed to have been previously specified by the landing parameter selection procedure identified in Table 4.1, in accordance with Tables 2.1, 2.2, and 2.3 of Chapter 2.

Heading Maneuvers

Table 4.4 summarizes the heading maneuver procedures in a similar format.

The first entry indicates that heading maneuvers will be initiated in response to ATC vector requests. The commanded heading is simply that requested by ATC; the turn rate is a standard 3 deg/sec, with the sign chosen to minimize the total heading change.

The second entry corresponds to a flight manual final approach procedure. It is triggered by localizer activity and the intent is to ensure that the final approach heading coincides with the inbound localizer heading; ψ_{LOC}. The rate command, $\dot{\psi}_{final}$, is not fixed, but assumed to be calculated so as to ensure that, at the end of the turn maneuver, the vehicle ground track tangentially intercepts the localizer plane (i.e., $\psi = \psi_{LOC}$ when $\epsilon_{LOC} = 0$).

Flare Maneuvers

Table 4.5 summarizes the flare maneuver procedures in a similar format.

The first entry is triggered by being 0.5 dot below the glide slope. The commanded flight path angle is chosen to equal the negative of the glide slope elevation angle; the rate command, $\dot{\gamma}_{final}$, is not fixed, but assumed to be calculated so as to ensure

Table 4.4: Heading Maneuver Procedures

TRIGGER CONDITION	COMMAND	RATE COMMAND
1. ATC TURN REQUEST	$\psi_{cmd}=\psi_{ATC}$	$\dot{\psi}_{cmd}=\pm$ 3 deg/sec
2. LOC ACTIVE	ψ_{LOC}	$\dot{\psi}_{final}$

Table 4.5: Flare Maneuver Procedures

TRIGGER CONDITION	COMMAND	RATE COMMAND
1. $\varepsilon_{GS}=-0.5$ deg	$\gamma_{cmd}=-\theta_{GS}$	$\dot{\gamma}_{cmd}=\dot{\gamma}_{final}$
2. $h = 50$ ft	0	$\dot{\gamma}_{flare}$

Table 4.6: Altitude Maneuver Procedure

TRIGGER COMMAND	COMMAND	RATE COMMAND
ATC CLIMB/DESCENT REQUEST	i) $\gamma_{cmd}=-\dot{h}_c/v_c$	i) $\dot{\gamma}_{cmd}=\pm$ 0.2 deg/sec
	ii) $h_{cmd}=h_{fo}$	ii) $\dot{h}_{cmd}=\dot{h}_c$
	iii) $\gamma_{cmd}=0$	iii) $\dot{\gamma}_{cmd}=\pm$ 0.2 deg/sec

note 1: if ATC requests DESCENT, $\dot{h}_c = \begin{matrix} -30\text{ft/s} & \text{if } h>5000\text{ ft} \\ -15\text{ft/s} & \leq 5000\text{ ft} \end{matrix}$

note 2: $h_{fo} = f(h_c, v_c)$

that, at the end of the flare, the vehicle is on the glide slope (i.e., $\gamma = -\theta_{GS}$ when $\varepsilon_{GS}=0$).

The second entry is triggered by a 50 ft AFE altitude and is intended to ensure a final flare which results in zero sink rate at zero altitude, via an appropriate choice of the free parameter $\dot{\gamma}_{flare}$.

Altitude Maneuvers

Table 4.6 summarizes the one climb/descent procedure required for the approach.

In response to an ATC climb or descent request to a specified altitude h_c, three maneuver sub-commands are generated. The first is a flare command, with γ_{cmd} chosen to achieve the desired climb/sink rate ($\dot{h}_c$), assuming the vehicle is maintaining its current velocity (v_c). The nominal sink rate $\dot{h}_c$ is procedurally specified as a function of current altitude, as shown in the table. The flare rate associated with this first sub-command is fixed at 0.2 deg/sec, with the sign chosen appropriately. The second sub-command is an altitude command to a flare-out altitude, h_{fo}. This flare-out altitude is calculated to ensure that the commanded altitude, h_c, is attained at the end of the flare-out. The third sub-command is the flare-out command, again incorporating a fixed flare rate of 0.2 deg/sec.

4.2.2 "Regulatory" or "Closed-Loop" Control

In order to maintain the nominal or desired approach the PF must compensate for disturbances. This is especially important in a non-coupled final approach. The regulatory or closed-loop control task is one for which the standard OCM is particularly appropriate. However, we must account for this task being one of several competing for the PF's attention.

Following the OCM, we assume that the PF's (perturbation) control actions in regulating about the nominal, are given by

$$\underline{u}(t) = \underline{L}_{N_i}(t)\hat{\underline{x}}(t) \qquad (4.1)$$

where $\hat{\underline{x}}(t)$ is PF's estimate of the perturbation state and $\underline{L}$ is the matrix of control gains chosen to minimize a quadratic cost function in error and control variables of the form:

$$J = \left(\frac{v}{v_{max}}\right)^2 + \left(\frac{\psi}{\psi_{max}}\right)^2 + \left(\frac{\gamma}{\gamma_{max}}\right)^2 + \left(\frac{h}{h_{max}}\right)^2 + \left(\frac{\varepsilon_{LOC}}{\varepsilon^{max}_{LOC}}\right)^2$$
$$+\left(\frac{\varepsilon_{GS}}{\varepsilon^{max}_{GS}}\right)^2 + \left(\frac{\alpha}{\alpha_{max}}\right)^2 + \left(\frac{T}{T_{max}}\right)^2 + \left(\frac{\phi}{\phi_{max}}\right)^2 \qquad (4.2)$$

Note that the control gains depend on the nominal segment being flown. They also can be time varying within a segment if the system matrices change (as in a turn) or if the weightings vary with time or range (as in the final approach).

As noted earlier, the weightings for the cost function (4.2) are chosen whenever the maneuver procedure is executed (recall step 3 of Table 4.2). The use of estimated maximum allowable deviations in defining the weightings is standard practice in applying the OCM [3]. The particular values selected for these maxima were based on the literature, an examination of the cockpit instrumentation and "educated guesses". The weightings are assumed to vary with approach progress and segment type as shown in Tables 4.7, 4.8 and 4.9. Table 4.7 shows how the state/display-associated weightings are selected on the basis of approach progress, and Table 4.8 shows how selected weightings are modified on the basis of the maneuver being executed. Finally, Table 4.9 defines the control-associated weightings, as functions of maneuver-type.

The other aspect of the closed-loop control procedure that must be specified is the manner in which the pilot shares attention among the displays of interest. We have assumed that this is done in accordance with the following sub-optimal algorithm. It can be shown that, in steady-state, the portion of J related to the operator's observation noise (and, therefore, to the attentions) is given by [7]

$$\tilde{J}(V) = \mathrm{Tr}\ \{\underline{L}^T \underline{Q}_u \underline{L}\, \underline{\Sigma}(V)\} \qquad (4.3)$$

Table 4.7: State/Display Weightings vs. Approach Progress

Weighting \ Approach Progress	Before LOC Intercept	After LOC Intercept & Before GS Intercept	After GS Intercept
v_{max}(kt)	3	3	3
ψ_{max}(deg)	1.5	∞	∞
γ_{max}(deg)	1.0	1.0	1.0
h_{max}(ft)	300	300	∞
ε_{LOC}^{max}(dot)	∞	0.33	0.33
ε_{GS}^{max}(dot)	∞	∞	1.00

Table 4.8: State/Display Weighting Modifications vs. Maneuver

Maneuver	Weighting Modification
DECEL	$v_{max} = v_{max}/3$
TURN	$\psi_{max} = \psi_{max}/3$
FLARE	$\gamma_{max} = \gamma_{max}/3$
DSCNT	$h_{max} = h_{max}/3$
S&L	------

Table 4.9: Control Weightings vs. Maneuver

Maneuver / Weighting	DECEL	FLARE	DSCNT	TURN/ S & L
T_{max}(lb)	5000	50,000	5000	2500
α_{max}(deg)	10	0.5	5	2.5
ϕ_{max}(deg)	2.5	2.5	2.5	2.5

where $\underline{L}$ is the control gain (4.1), $\underline{\Sigma}$ the estimation error covariance and $\underline{Q}_u$ is the control-weighting matrix in the cost functional. Thus, the estimation errors are weighted by their importance for the control objectives. Now, it is easily shown that the reduction in uncertainty obtained by "sampling" the i^{th} display at time k is*

$$\Sigma_{k/k-1} - \Sigma_{k/k} = \Sigma_{k/k-1} C_i' [C_i \Sigma_{k/k-1} C_i' + \frac{V_{y_i}}{\Delta}]^{-1} C_i \Sigma_{k/k-1} \quad (4.4)$$

where C_i is the i^{th} row of the display matrix (Eqn. 3.6), $\Sigma_{k/k-1}$ is the uncertainty at time k if no observation is made, $\Sigma_{k/k}$ is the uncertainty with observation of display i, V_{y_i} is the observation noise associated with display i (Eqn. 3.7) and Δ is the interval between samples.

Equation (4.4) may be thought of as the monitoring gain for observing display i. However, we are interested in the gain for observing display i with respect to control objectives, so we substitute (4.4) in (4.3) to obtain

$$J_i = \mathrm{Tr}\{\underline{L}^T \underline{Q}_u \underline{L} \Sigma_{k/k-1} C_i' [C_i \Sigma_{k/k-1} C_i' + \frac{V_{y_i}}{\Delta}]^{-1} C_i \Sigma_{k/k-1}\} \quad (4.5)$$

If we were to implement a pure scanning strategy, we would simply assume PF monitors the display for which J_i is a maximum. Here, instead, we use a "mixed" scanning strategy and define fractional attentions by

* We use the discrete Riccati equation for estimation [8]. We also assume no rate information obtained from the display but this is easily changed.

$$f_i = \frac{J_i}{\Sigma J_i} \tag{4.6}$$

Should any of the f_i's defined by (4.6) fall below .01, we set them to .01 and modify the remaining attentions in an appropriate manner. The monitoring algorithm just described actually is in operation during maneuver control and retrim as well, so long as another monitoring request has not been made.

A question arises in the multi-task environment: "What is the control law when another task is being performed?". We shall assume that control is continuously applied according to (4.1). The effect of executing another procedure will not be one of interrupting control, but rather, one of diverting attention from the observation of those variables needed for control. This will necessitate using predicted values for $\underline{x}$ in (4.1), during the interval of interrupted observation, resulting in an "open-loop" perturbation control until the vehicle control procedure is invoked again.

4.2.3 Retrim Procedure

This procedure is also assigned to the PF, and has as its basic objective the retrimming of the vehicle whenever flap or gear settings change the trim conditions. Since no maneuvers are involved, this procedure can be simply summarized as shown in Table

Table 4.10: Retrim Procedure (PF)

Step	Action
1	Solve for trim controls (T_c, α_c, ϕ_c)
2	Set trim controls

4.10. As in the maneuver procedure, the trim controls are obtained by use of an algorithm based on the solution outlined in section C.7 of Appendix C.

4.2.4 Monitor Procedure

This constitutes procedure category 1 for PNF, as shown in Table 4.1. The background or default monitoring is to determine vehicle status and to detect failures or events. Monitoring for approach progress has been associated with callout procedures.

Monitoring for status determination could involve attention sharing to minimize uncertainty in a manner similar to that of the closed-loop control procedure (but without the control gain weights). Monitoring for failure or event detection and identification might be predicated on the relatively sophisticated algorithms discussed in [1,6,9]. In this initial investigation with PROCRU, we assumed that PNF shares attention among flight instruments so as to minimize uncertainty (i.e., Tr $\underline{\Sigma}$) when exercising the monitoring procedure.

4.2.5 PF Request Procedures

The verbal requests made by the PF include calling for appropriate flap settings, lowering of the gear, and initiating checklists.

The flap request procedure is summarized in Table 4.11. Note that all the triggering conditions involve the vehicle velocity reaching some "setpoint" velocity (from above), and all of the procedural actions involve a verbal request to the PNF. The two unspecified parameters are assumed to have been previously specified by the landing parameter selection procedure identified in Table 4.1, in accordance with Tables 2.2 and 2.3 of Chapter 2.

The gear request procedure is defined by Table 4.12. When the vehicle is 2 dots below the glide slope, a lower gear request to the PNF is called for.

Table 4.11: Flap Request Procedure (PF)

TRIGGER CONDITION	ACTION*
v=190 kt	"set flaps to 2 deg"
160 kt	5
150 kt	15
140 kt	25
v_{app}	δ_{LF}

*verbal request from PF to PNF

Table 4.12: Gear Request Procedure (PF)

TRIGGER CONDITION	ACTION*
ε_{GS}=-2 dot	"lower gear"

*verbal request from PF to PNF

The procedure for requesting initiation of the initial approach checklist (IAC) and the final approach checklist (FAC) is given in Table 4.13. Both triggering conditions involve the vehicle altitude reaching some "setpoint" altitude (from above), and both procedural actions involve a verbal request to the SO.

4.2.6 PNF Callout Procedure

The verbal callouts made by the PNF include calling out vehicle approach progress and approach stability.

The vehicle approach progress callout procedure is summarized in Table 4.14. The first four items have trigger conditions associated with the ILS beacon system, and result in a verbal indication to the PF of vehicle position relative to the ILS geometry. The last four items are altitude callouts, and are predicated on vehicle height AFE and the selected decision height (h_{DH}), the latter assumed to have been previously specified by the landing parameter selection procedure. As noted in Chapter 2, the decision height for this study was fixed at 200 ft. The altitude callouts are used by PF as discrete measurements to update PF's estimate of altitude.

The approach stability callouts made by the PNF have already been detailed in Table 2.7 of Chapter 2.

Table 4.13: Checklist Initiation Request Procedure (PF)

TRIGGER CONDITION	ACTION*
h = 3500 ft	"start IAC"
2000 ft	"start FAC"

*verbal request from PF to SO

Table 4.14: Approach Progress Callout Procedure (PNF)

TRIGGER CONDITION	ACTION*
1. LOC ACTIVE	"localizer capture"
2. GS ACTIVE	"glide slope alive"
3. OM ACTIVE	"outer marker"
4. MM ACTIVE	"middle marker"
5. $h = 1000$ ft	"1000 ft"
6. $h = 500$ ft	" 500 ft"
7. $h = h_{DH}+100$ ft	"approaching minimums"
8. $h = h_{DH}$	"minimums"

*verbal callout from PNF to PF

4.2.7 Subsystem Monitoring and Control Procedures

As noted earlier, the subsystem monitoring and control procedures for the PF can be conveniently separated into those dealing with the altitude alert (AA) subsystem, and those dealing with other subsystems.

The altitude alert servicing procedure is summarized in Table 4.15. The first entry indicates that ATC descent requests will trigger AA servicing. The servicing involves paying almost full attention to the AA while setting the alert altitude, h_{AA}, on the basis of the requested descent altitude and a scale factor K, which, for our study was set to 1.15. This provided for AA alarm turn-on at an altitude 15% higher than the requested descent altitude.

The second entry indicates that similar AA servicing will be triggered by passage of the OM. Here the alert altitude h_{AA} is specified to be set to the decision height h_{DH}.

The final entry provides for AA alarm servicing. Again, this implies a diversion of attention from flight displays while the alarm is turned off.

Other miscellaneous subsystem servicing procedures assigned to the PF (and PNF) are summarized in Table 4.16. The trigger

Table 4.15: Altitude Alert Subsystem Servicing Procedure (PF)

TRIGGER CONDITION	ACTION
1. ATC DSCNT REQUEST ($h_{cmd} = h_{ATC}$)	set $h_{AA} = Kh_{ATC}$
2. OM ACTIVE	set $h_{AA} = h_{DH}$
3. AA ALARM "on"	set AA ALARM "off"

Table 4.16: Subsystem Servicing Procedure (PF/PNF)

TRIGGER CONDITION	ACTION BY	ACTION
1. FIRST ATC REQUEST	PF PNF	turn continuous ignition "on" turn seat belt sign "on"
2. $\varepsilon_{GS} = -0.5$ dot	PF	speed brake lever "arm"
3. speed brake lever armed	PF	turn no smoking sign "on"
4. no smoking sign "on"	PF	turn antiskid system "on"
5. ATC CFL	PF	check GPWS

conditions and actions are self-explanatory. Note that all of the actions require a diversion of attention, away from the primary flight control displays and towards the appropriate subsystem being serviced.

The final category of subsystem servicing procedures are those concerning flap and gear settings performed by the PNF, which are

Table 4.17: Flap/Gear Subsystem Servicing Procedure (PNF)

TRIGGER CONDITION*	ACTION
1. "set flaps to ___ deg"	i) check speed/flap table ii) set flap handles iii) confirm flap setting
2. "lower gear"	i) set gear handle ii) confirm gear down iii) confirm doors open

*verbal request from PF to PNF

summarized in Table 4.17. The first item shows the verbal flap request made by the PF triggering three actions: a validation concerning the appropriateness of the request; a setting of the flap handles; and a confirmation of the flap handle setting with the associated indicator lights. All three actions divert attention from the flight displays. In addition, the actual setting of the flaps affects the vehicle dynamics (as described in

Appendix C) so that a requirement is placed on the PF to retrim the vehicle (via the retrim procedure discussed earlier).

The second item shows a similar verbal request trigger which results in three actions: a setting of the gear handle, and two subsystem confirmations. Again, these are all modelled as attention "sinks", and the actual gear lowering drives the vehicle dynamics, similarly requiring a retrimming by the PF.

4.2.8 Acknowledgement Procedure

The verbal acknowledgements made by the PF and PNF involve responses to checklist item prompts made by the SO. In addition, the PNF is required to respond to and acknowledge ATC vectoring requests.

The acknowledgement procedure is summarized in Table 4.18. The first item is conditioned by a checklist item prompt by the SO. The intended recipient of that prompt is then required to monitor the appropriate subsystem associated with the checklist item (an attention sink), and verbally respond with a confirmation of subsystem validity.* Currently, nine checklist item prompts are targeted for the PNF, and one for the PF. The second item is similarly structured, involving a confirmation by the PNF of the

* In this study, we assume no subsystem failures.

Table 4.18: Acknowledgement Procedure

	TRIGGER CONDITION	ACTION BY	ACTION
1.	SO: "subsystem ___ OK?"	PF PNF	i) monitor subsystem ___ ii) "subsystem ___ OK"
2.	ATC REQUEST	PNF	"confirm..."

ATC vector request. No subsystem monitoring is required here, however.

4.2.9 SAP/MAP Terminal Procedures

The SAP/MAP terminal procedures include appropriate callouts, decisions on display monitoring strategy, and control actions. Although operationally considered different procedures, both the SAP and MAP can be conveniently summarized as shown in Table 4.19.

The first item indicates that, for either procedure, the PNF begins monitoring the external scene at a "search height" h_{SH}. In accordance with operational manual dictates, we assume that the PNF divides his attention equally between the external scene and the instruments, in order to maintain back-up monitoring capability while searching for visual landing cues.

Table 4.19: SAP/MAP Terminal Procedures

TRIGGER CONDITION	ACTION BY	ACTION
1. $h = h_{SH}$	PNF	begin monitoring external scene
2. RWIS & monitoring external scene	PNF PNF	SAP: "runway in sight" MAP: "taking control"
3. "runway in sight"	PF PNF	monitor external scene monitor instruments
4. "taking control"	PF PNF	take control of vehicle relinquish control of vehicle
5. $h = h_{DH}$ & no "RWIS" callout & no "taking control" callout	PF	i) "executing missed approach" ii) execute missed approach
	PNF	i) monitor instruments ii) execute missed approach

If the PNF observes the runway while monitoring the external scene, the SAP dictates a "runway in sight" callout, while the MAP dictates a "taking control" callout, as shown by item 2.* Items 3 and 4 show the appropriate follow-on action for each of these callouts.

If no callout has been made by the time the vehicle reaches the decision height, h_{DH}, then item 5 provides for the PF to announce and execute a missed approach while the PNF switches to instruments and assists in the missed approach. The missed approach procedure itself has already been outlined in Table 2.12 of Chapter 2.

It should be noted that the SAP/MAP procedures outlined above are considerably simplified from those outlined and discussed in Chapter 2. This has been done for the purpose of modelling simplicity, but an attempt has been made to retain the essential monitor and control aspects which differentiate the two basic approach procedures.

Table 4.19 requires the specification of two height parameters, and a definition of RWIS. The "search height" h_{SH} was specified to be 300 ft; the decision height, h_{DH} was set at 200 ft.

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* For simplicity, we assume the vehicle to be appropriately positioned for a VFR landing when the runway is in sight.

The RWIS condition was determined simply by specifying a "breakout" altitude of 250 ft.

4.3 Expected Gain Functions for Procedures

As discussed in Chapter 3, each of the procedures just described has associated with it an expected gain EGP(I) for determining the "value" of executing that procedure at any given time during the approach. This section defines the EGP's associated with each of the procedures and provides a rationale for these definitions.

4.3.1 General Form of EGP Function

In Chapter 3, we defined the EGP(I) function as

$$EGP(I) = G(I) + G_o(I) \tag{4.7}$$

where G(I) is a function related to the relevance of executing the Ith procedure and $G_o(I)$ is a constant chosen to reflect the baseline value of the procedure, independent of its situational relevance. It is useful to write G as the product of two functions, i.e.*

* For convenience, here and subsequently, we do not show the dependence on procedure number explicitly.

$$G = U * R \tag{4.8}$$

where R is a function of the relevance of the procedure and U is, for this initial implementation of PROCRU, a unit step function that is one when the procedure is "enabled" by an appropriate event and is zero otherwise.*

For all of the procedures considered in this study, one of three generic functional forms is used to specify the R component of the EGP. We discuss these functions in the following paragraphs.

One of the generic functions which we call a "timeliness" function, T, is applicable to procedures which are "event driven". If we assume a procedure should be executed immediately after, or within a short time following, the occurrence of the event e, then the corresponding relevance function should be predicated on the time of event occurrence, t_e. Equation 4.9 shows such a functional dependence.

$$T = \begin{cases} 0 & \text{if } t<t_e \\ 1-e^{(t-t_e)/\tau} & \text{if } t_e< t< t_e + .69\tau \\ 1 & \text{if } t\geq t_e + .69\tau \end{cases} \tag{4.9}$$

* In future work, U could be a more sophisticated "utility" function.

Prior to the "event time" t_e, T is zero; after that time, it grows exponentially, with a time-constant τ, appropriate for that procedure, to a limiting value of unity.

The type of procedures utilizing this general function are those which are "triggered" by discrete events: the PNF's verbal acknowledgement of a verbal ATC vector request; the PF's turning off of the altitude alert alarm, the PNF's callout of localizer activity, etc.

The other two generic R functions, called "appropriateness" functions, A, are intended for use with procedures which are triggered by the satisfaction of one or more vehicle state/display conditions (e.g., the gear lowering request made by the PF when the vehicle is 2 dots below the glide slope). For a crewman to determine when such a procedure is "appropriate", calculation of the subjective probability that the procedure's triggering condition is satisfied is required. Since a high probability indicates that procedure execution is highly appropriate, and conversely with a low probability, the probability calculation provides a direct measure of "appropriateness" on a zero to one scale.

If a procedure is to be triggered when a particular state variable that is changing monotonically reaches a predetermined

value, we may define an "appropriateness" function by the expressions

and

$$\left.\begin{aligned} A_1 &= \Pr\left\{x_j < x_{j_{SP}} + x_{j_T}\right\}, \dot{x}_j < 0 \\ &= \Pr\left\{x_j > x_{j_{SP}} - x_{j_T}\right\}, \dot{x}_j > 0 \end{aligned}\right\} \qquad (4.10)$$

where x_j is the appropriate state variable for the procedure, $x_{j_{SP}}$ is the trigger or set-point value and x_{j_T} is a tolerance level added to provide some "anticipation". The subjective probability calculation implied by (4.10) is based on the crew member's estimate of the state and the uncertainty in that estimate. The probability function (A_1) will continue to increase monotonically as the set-point is approached and passed; it will have a value of .5 when the estimate of the state equals the set-point plus the tolerance. Thus, this functional form implies that the procedure never becomes inappropriate once the trigger conditions have been met; i.e., the procedure should still be executed even if late.*

Examples of procedures utilizing this appropriateness function are the altitude callouts by the PNF, the velocity-triggered flap requests made by the PF, and the glide-slope dependent speed-brake

* However, if the procedure is executed, or if for some other reason it becomes inappropriate to execute, the U function can be set to zero.

subsystem servicing performed by the PF. The various set-points are the trigger values given in the tables describing the procedures.

A second, slightly modified, form for the appropriateness function is used when the procedure is driven by a "window" requirement on the state; i.e., if a procedure is triggered when the state enters or "escapes", or is about to enter or escape, some window of acceptability. For such a procedure, we use a two-sided probability calculation for the "appropriateness" function:

$$A_2 = 1-\Pr\left\{x_{j_{SP}} - x_{j_w} \leq x_j \leq x_{j_{SP}} + x_{j_w}\right\} \tag{4.11}$$

The A_2 function is used for the EGP calculation associated with the regulatory procedure (with $x_{J_w} = .5x_{j\max}$, where $x_{j\max}$ is the value used in computing the corresponding cost functional weighting) and for the procedure for approach destabilization callouts.

Tables 4.20a and 4.20b summarize the parameters associated with the procedures defined for PF and PNF. Shown are the enabling events and the function type and parameter values for the EGP functions. Also shown are the nominal lock-up times associated with execution of each procedure (see below).

4.4 Procedure Execution

In terms of execution, it is useful to separate the procedures into two classes, those that require a condition or predicate to be satisfied before an action is taken, and those that don't.

Table 4.20a: Procedural Parameters, PF

PROCEDURE	ENABLING EVENT	PRIORITY VALUE G_o	GAIN TYPE R*	GAIN FUNCTION PARAMETER**	LOCK-UP TIME (sec)
1. Msg Decode	any audio activity		T	alarm: 0 other: 5.0	0.2
2. IAC request	detects $h < h_{iac}$		T	15.0	1.0
3. FAC request	detects $h < h_{fac}$		T	15.0	1.0
4. Re-trim	doing a maneuver		A_1	$\dot{x}_n$*dt	2.0
5. Process an ATC command	ATC msg decoded		T	5.0	2.0
6. Flaps request	detects $V \approx V_{FLAP}$		A_1	0	2.0
7. Respond to S/O prompt "landing gear down?"	S/O prompt decoded		T	5.0	2.0
8. Respond to RWIS callout	RWIS callout decoded		T	0	3.0
9. Set Altitude † alert	Chg Alt. command decoded		T	0	2.0
10. Set inboard † I.L. on	not implemented		T	5.0	2.0
11. Set cont. ign. † on	not implemented		T	5.0	2.0
12. Set speed † brakes armed	not implemented		T	5.0	2.0
13. Set no smoking † sign on	not implemented		T	5.0	2.0
14. Set anti skid † on	not implemented		T	5.0	2.0
15. Set GPWS on †	not implemented		T	5.0	2.0
16. Gears down request	2 dots below GS		T	5.0	2.0
17. Flare to GS-trim	1/2 dot below GS		T	0	2.0
18. Flare to TD-trim	detects h < 50		A_1	$\dot{h}_n$*dt	2.0
19. Turn onto LOC-trim	detect LOC "on"		T	5.0	2.0
20. Decel to 150-trim	Cleared for landing		T	5.0	2.0
21. Decel to 140-trim	1.5 dots below GS		T	5.0	2.0
22. Decel to 139-trim	1.0 dots below GS		T	5.0	2.0
23. Decel to 134-trim	detect h < 150'		A_1	160	2.0
24. Set Alt. Alert off	AA alarm decoded		T	5.0	2.0
25. Execute missed approach	Missed approach callout decoded		T	5.0	2.0
26. Fly	always enabled	.3	A_2	$x_{max}/2$	0.2
27. Process Alt. callouts	Alt. callout decoded		T	0	0.2

*Type of "relevance" function

**For T functions, the parameter is the time constant (in seconds) of Eqn. 4.9. For A_1 functions, the parameter is the tolerance level added to the set point (x_T of Eqn. 4.10). For A_2 functions the parameter is the window value (x_w of Eqn. 4.11).

†Not currently implemented.

Table 4.20b: Procedural Parameters, PNF

PROCEDURE	ENABLING EVENT U	PRIORITY VALUE G_c	GAIN TYPE R*	GAIN FUNCTION PARAMETER**	LOCK-UP TIME (sec)
1. Msg Decode	any audio activity		T	alarm: 5 other: 5.0	0.2
2. LOC callout	LOC alarm decoded		T		1.0
3. GS callout	GS alarm decoded		T	5.0	1.0
4. OM callout	OM alarm decoded		T	5.0	1.0
5. MM callout	MM alarm decoded		T	5.0	1.0
6. Runway in sight equation	detects $h = h_{SM}$		T	5.0	10.0
7. -	-		-	-	-
8. Respond to flaps request	Flap request decoded		T	5.0	4.0
9. Respond to gear request	gear request decoded		T	5.0	4.0
10. Acknowledge ATC Respond to S/O Prompts...	ATC msg decoded		T	5.0	1.0
11. "Cont. ignition on?"	S/O prompt decoded		T	5.0	4.0
12. "Seat belt on?"	"		T	5.0	4.0
13. "A,F,&M instrument check"	"		T	"	4.0
14. "RA/Boro, Alt. bug check"	"		T	"	4.0
15. "Air&EPR bug check"	"		T	"	4.0
16. "No smoking sign on"	"		T	"	4.0
17. -	-		-	-	-
18. "Approach flaps set?"	"		T	"	4.0
19. "Tail skid light off?"	"		T	"	4.0
20. "Speed brakes armed?"	"		T	"	4.0
21. Approach stability monitor	OM alarm decoded		T	"	2.0
22. Status monitor		.3	A_2	$x_{max}/2$	0.2
23. 1000' Alt. callout	detects $h = h_{1000}+25$		A_1	25	2.0
24. 500' Alt. callout	detects $h = h_{500}+25$		A_1	25	2.0
25. Approaching minimum callout	detects $h = h_{min}+25$		A_1	25	2.0
26. Minimum callout	detects $h = h_{min}+25$		A_1	25	2.0

*Type of "relevance" function

**For T functions, the parameter is the time constant (in seconds) of Eqn. 4.9. For A_1 functions, the parameter is the tolerance level added to the set point (x_T of Eqn. 4.10a). For A_2 functions the parameter is the window value (x_W of Eqn. 4.11).

If no predicate is specified, an appropriate control, monitoring or communication action will immediately follow the selection of a procedure. The only exception to this is the message decode procedure which can have as its output the "enabling" of a subsequent procedure. Examples of procedures without predicates are the default procedures of regulatory control and monitoring and some event-driven procedures, such as check list execution.

If a procedure has a predicate for execution, then the first step of the procedure involves a check to determine the situation with respect to this predicate. In the case where the predicate is a discrete event, the event detector is checked to see whether or not the requisite event has occurred. If so, action is taken; if not, the procedure is exited. Usually, however, the predicate condition is one on a vehicle state variable. In this case, what ensues upon the selection of such a procedure is determined by the level of the procedural appropriateness function, A, as follows:

$$A < P_{MON} \quad \text{exit procedure} \tag{4.12a}$$

$$P_{MON} < A < P_{ACT} \quad \text{monitor request} \tag{4.12b}$$

$$A > P_{ACT} \quad \text{control action} \tag{4.12c}$$

Equation 4.12a is included to account for the possibility that a procedure may have the highest gain and yet still not be sufficiently close to the triggering condition, in the operator's estimation, to warrant action. This could happen during a "relaxed" portion of the approach. When the probability of satisfying the condition (as determined by A) exceeds a monitoring threshold (P_{MON}), but is less than an action threshold (P_{ACT}), a monitoring request is issued. This results in full attention being devoted to the "display" to be monitored,* so as to reduce the uncertainty in the corresponding estimate and thereby increase the likelihood that an action/no action decision will be made subsequently. If Eqn. (4.12c) is satisfied, the appropriate discrete action (set flaps, extend gear or make callout) is then taken. We note that either type of appropriateness function, A_1 or A_2, may be used in establishing the predicate, depending on the procedure.

The other important aspect of procedure execution is that each action is assumed to take some specified time, during which no other activity takes place. The "lock-up times" used in this initial implementation of PROCRU are, essentially, "reasonable guesses". The specific values are given in Table 4.20.

* Here, full attention corresponds to 95% for numerical reasons.

5. SIMULATION RESULTS

In this chapter, we present results to illustrate the operation and capabilities of the PROCRU model. Sensitivity of model results to selected variations in system and operator parameters is examined briefly.

5.1 Simulation Conditions

5.1.1 System Variables

We will consider two approach scenarios starting from the same initial conditions (Figure 2.2, 2.3). One scenario, ATCLO, a low workload approach, is essentially the nominal approach described in Chapter 2; the other, ATCHI, is a higher workload scenario in which the tempo is increased by having the final segment shortened by an early turn towards the localizer.* The ATC commands for the two scenarios are given in Table 5.1.

For this analysis, we have not attempted to model wind disturbances in any realistic fashion. Instead, we have simply added zero-mean white gaussian noise sequences in parallel with each of the control inputs. Two values for the covariances of the noise sequences were used in the analysis:

* But late with respect to time to touchdown.

Table 5.1: ATC Commands for Approach Scenarios

COMMAND	TIME (seconds)	
	NOMINAL	HIGH WORKLOAD
TURN to 270^{o}	0	0
DECEL to 170 kts	30	30
DESCEND to 3500'	50	50
DECEL to 160 kts	310	310
TURN to 180^{o}	440	365
DESCEND to 2000'	480	405
TURN to 120^{o}	530	500
CLEARED for landing	605	530

$$\text{LOW}: \; W_\phi = (1 \text{ deg})^2 \; ; \; W_\alpha = (.1 \text{ deg})^2 \; ; \; W_T = (200 \text{ lbs})^2$$

$$\text{HIGH}: \; W_\phi = (6 \text{ deg})^2 ; \; W_\alpha = (.6 \text{ deg})^2 ; \; W_T = (1200 \text{ lbs})^2$$

where the subscript on the covariance indicates the (control) input injection point of the noise.* These two sets of values arc considered so as to span a range of approach difficulty.

5.1.2 Crew Variables

With respect to crew variables, we will consider variations in observation noise (a workload related parameter [5]), in procedure "lock-up" times, and in the base priority level (G_o) for performing the default procedures of flying (for PF) and monitoring (for PNF).

The base value for PY in Eqn. (3.7) is set at -20 dB, a value obtained in laboratory tracking experiments in which subjects were devoting full attention (or a large amount of attention) to the task [2]. Nominal thresholds for instruments were set at zero, but the constant components of observation noise, which have a similar effect, were non-zero (see Eqn. (3.7)). In particular, the constant values were set at:

* The noise levels correspond to control input levels in that the noise disturbance is multiplied by the control injection matrix B (see Eqn. (3.5)).

$V^o_h = (25\ ft)^2$ $\quad V_{\dot{h}} = (.5\ ft/sec)^2$

$V^o_v = (.5\ kt)^2$ $\quad V^o_{LOC} = (.2\ dot)^2$

$V^o_\psi = (.5\ deg)^2$ $\quad V^o_{GS} = (.33\ dot)^2$

Thresholds for the external scene were set to the values in Appendix D; constant noises for the external scene were set to zero.

The above observation noise parameters were assumed to correspond to full attention. The observation noise was also doubled to correspond to a case in which less (one-half) attention is devoted to the modelled task (perhaps because of inner loop control requirements or less motivation).

Base lock-up times and other parameters for the various procedures are those shown in Table 4.20. Base values for P_{MON} and P_{ACT} in Eqn. (4.6) were chosen to be .8 and .95, respectively. To explore the effects of some of these parameters, variations in lock-up times and in the base gain value of the default procedures were considered. A simulation was run in which all lock-up times were increased by approximately 50%. In another case, default gain values were increased from .3 to .6.

5.1.3 Procedural Variables

The only procedural variation examined here is between basic SAP and MAP procedures as defined in Section 4.2.9.

5.2 PROCRU Outputs

PROCRU generates a number of outputs that are useful for analyzing crew procedures and performance. First, one can obtain full trajectory information. This information is provided at any time in terms of the total state (TSTATE xt) (and/or the nominal state) and the perturbation or deviation (DSTATE x) from the nominal. In addition to this information, one can obtain each crew member's estimate of the state (xh) and the standard deviation of the estimation error (SDEV), the attentional allocation (AT) at that time and PF's control inputs (u). These data, along with significant events, etc., are tabulated in an ANS (answer) file as illustrated in Figure 5.1. The ordering of state and control information, from left to right, is $(x, y, h, v, \psi, \gamma)$ and $(\phi, \alpha, T,$ Flaps, Gear). PF is crew member 1 and PNF crew member 2.

In addition to the ANS output, PROCRU provides three separate time lines: a procedural time line (PTL), a message time line (MTL), and a milestone time line (TL). Table 5.2 lists the mnemonics used for these time lines. The procedural time-line, illustrated in Figure 5.2 for the nominal approach conditions, provides a listing of the procedures (PROC) being executed by each

Figure 5.1: Sample PROCRU Trajectory Information File (Case 1LS)

```
*** TIME= 5.816E+02 ***
Tstate xt: 1.489E+04-8.619E+04 2.091E+03 1.599E+02 1.799E+02-2.942E+00
Dstate x:  1.278E-01 3.205E-01 1.832E-01-8.564E-02-7.831E-02 3.503E-02
xh1 k|k:   1.263E+00 1.221E+00-2.772E-01 1.923E-02 5.370E-02-2.596E-02
xh2 k|k:   9.636E-01-3.556E+00-4.201E-01 5.574E-02-7.441E-03 3.323E-02
SDev1 k|k: 1.251E+02 1.092E+02 7.846E+00 1.971E-01 3.031E-01 8.459E-02
SDev2 k|k: 1.227E+02 1.081E+02 5.643E+00 2.192E-01 2.753E-01 1.084E-01
AT1:       V:   .015 PSI: .240 H:   .010 Hdot: .713 LOC: .010 GS:  .010
AT2:       V:   .086 PSI: .629 H:   .112 Hdot: .153 LOC: .010 GS:  .010
***** Altitude Alert Active *****
GUIDE: " Executing FLARE to  0.000E+00  deg  at  2.001E-01 deg/s "
Total u:  -8.950E-02 2.574E+00 9.398E+03 Flaps=  5. Gear is UP


*** TIME= 5.818E+02 ***
Tstate xt: 1.483E+04-8.619E+04 2.088E+03 1.599E+02 1.799E+02-2.864E+00
Dstate x:  1.605E-01 3.879E-01 2.360E-01-1.082E-01-6.467E-02 7.293E-02
xh1 k|k:   1.260E+00 1.172E+00-2.823E-01-4.249E-04 5.151E-02 1.534E-02
xh2 k|k:   1.432E+00-5.007E+00-1.348E-01 1.177E-02 4.980E-02 6.501E-02
SDev1 k|k: 1.251E+02 1.092E+02 7.847E+00 1.972E-01 3.080E-01 8.745E-02
SDev2 k|k: 1.227E+02 1.081E+02 5.644E+00 2.192E-01 2.753E-01 1.085E-01
AT1:       V:  0.000 PSI:0.000 H:  0.000 Hdot:0.000 LOC:0.000 GS: 0.000
AT2:       V:   .086 PSI: .628 H:   .112 Hdot: .154 LOC: .010 GS:  .010
***** Altitude Alert Inactive *****
GUIDE: " Executing FLARE to  0.000E+00  deg  at  2.001E-01 deg/s "
Total u:  -8.586E-02 1.955E+00 9.502E+03 Flaps=  5. Gear is UP

*** TIME= 5.820E+02 ***
Tstate xt: 1.478E+04-8.619E+04 2.086E+03 1.599E+02 1.799E+02-2.852E+00
Dstate x:  1.955E-01 4.469E-01 2.933E-01-9.887E-02-6.040E-02 4.449E-02
xh1 k|k:   1.258E+00 1.124E+00-2.789E-01 1.015E-02 4.942E-02-7.861E-03
xh2 k|k:   1.234E+00-4.404E+00-2.945E-02 1.631E-02 2.031E-02 5.046E-02
SDev1 k|k: 1.252E+02 1.092E+02 7.848E+00 1.972E-01 3.128E-01 9.021E-02
SDev2 k|k: 1.227E+02 1.081E+02 5.644E+00 2.192E-01 2.753E-01 1.085E-01
AT1:       V:  0.000 PSI:0.000 H:  0.000 Hdot:0.000 LOC:0.000 GS: 0.000
AT2:       V:   .086 PSI: .628 H:   .112 Hdot: .153 LOC: .010 GS:  .010
GUIDE: " Executing FLARE to  0.000E+00  deg  at  2.001E-01 deg/s "
Total u:  -8.236E-02 2.301E+00 9.606E+03 Flaps=  5. Gear is UP
```

Table 5.2: Mnemonics for Time Lines

FlapR	Flap request
GearR	Gear request
DCR	Begin descent checklist request
IACR	Begin initial approach checklist request
FACR	Begin final approach checklist request
OMA	Outer marker active callout
LOCA	Localizer capture callout
GslpA	Glide slope alive callout
AltCo	Altitude callout
AppDs	Approach destabilization callout
RwisC	Runway in sight callout
ATCcn	Confirmation of ATC msg.
DC#1	Descent checklist item #1
IAC#1	Initial approach checklist item #1
IAC#2	Initial approach checklist item #2
IAC#3	Initial approach checklist item #3
IAC#4	Initial approach checklist item #4
IAC#5	Initial approach checklist item #5
FAC#1	Final approach checklist item #1
FAC#2	Final approach checklist item #2
FAC#3	Final approach checklist item #3
FAC#6	Final approach checklist item #6
SBck	Speed brakes armed - check.
SBSon	Seat belt sign on announcement
FlapS	Flaps set announcement
Gear D	Landing gear down announcement
ILLon	Inboard landing lights on announcement

Table 5.2: (Cont.)

SBarm	Speed brakes armed
NSSon	No smoking sign on
ASon	Anti skid on
GPWon	Ground proximity warning system armed
AAon	Altitude alert on armed
AAoff	Altitude alert disarmed
LOCon	Localizer on
GSon	Glide slope on
OMon	Outer marker on
MMon	Middle marker on
GPWSa	Ground proximity warning system alert on
AltAl	Altitude alert on
Decel	Decel command
Turn	Turn command
Flare	Flare command
ChAlt	Change Altitude command
DCst	Starting descent checklist announcement
IACst	Starting initial approach checklist announcement
FACst	Starting final approach checklist announcement
DCfn	Finished descent checklist announcement
IACfn	Finished initial approach checklist announcement
FACfn	Finished final approach checklist announcement
ClrFl	Cleared for landing announcement
CIgON	Continuous ignition on announcement
MMa	Middle marker active callout

Figure 5.2: Sample PROCRU Procedure Time Line (case ILS)

	CAPTAIN (PF)				FIRST OFFICER (PNF)			
TIME	PROC:EGP	CLUST	DISP	PROC:EGP	PROC:EGP	CLUST	DISP	PROC:EGP
0.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
1.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
1.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
2.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
2.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
3.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
4.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
22.2	4: .97	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
24.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
31.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
31.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
32.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
32.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
33.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
34.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
51.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
51.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
52.0	4: .33	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .17
52.6	4: .33	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
53.6	4: .33	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
54.0	5: .85	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
56.0	9:1.00	Audio	SBsys	25: .30	22: .30	Instr	Scan	0: .00
58.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
83.4	4: .36	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
85.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
269.4	1:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	1: .10
269.6	26: .30	Instr	Scan	24: .04	22: .30	Instr	Scan	1: .14
270.4	26: .30	Instr	Scan	24: .22	1: .32	Audio	SBsys	22: .30
270.6	26: .30	Instr	Scan	24: .27	22: .30	Instr	Scan	0: .00
270.8	24: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
272.8	4:1.00	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
274.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
294.2	2: .31	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
295.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
302.6	4: .75	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
304.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
311.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
311.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
312.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
312.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
313.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
314.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
315.6	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
315.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	11: .04
317.0	26: .30	Instr	Scan	0: .00	11: .32	SBsys	SBsys	22: .30

Figure 5.2 (cont.)

321.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
322.0	4: .60	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
322.2	4: .60	Instr	V	26: .30	22: .30	Instr	Scan	0: .00
322.4	4: .60	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
324.0	6: .70	SBsys	SBsys	26: .30	22: .30	Instr	Scan	0: .00
325.2	6: .70	SBsys	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
325.4	6: .70	SBsys	SBsys	26: .30	22: .30	Instr	Scan	8: .04
326.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	8: .17
326.6	26: .30	Instr	Scan	0: .00	8: .32	Instr	V	22: .30
326.8	26: .30	Instr	Scan	0: .00	8: .32	SBsys	SBsys	22: .30
330.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
342.2	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
342.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	12: .04
343.6	26: .30	Instr	Scan	0: .00	12: .32	SBsys	SBsys	22: .30
347.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
368.8	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
369.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	13: .04
370.2	26: .30	Instr	Scan	0: .00	13: .32	SBsys	SBsys	22: .30
374.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
395.4	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
395.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	14: .04
396.8	26: .30	Instr	Scan	0: .00	14: .32	SBsys	SBsys	22: .30
400.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
422.0	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
422.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	15: .04
423.4	26: .30	Instr	Scan	0: .00	15: .32	SBsys	SBsys	22: .30
427.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
441.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
441.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
442.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
442.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
443.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
444.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
472.0	4: .60	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
474.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
481.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
481.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
482.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
482.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
483.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
484.2	9:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
486.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
497.8	4: .56	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
499.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
531.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
531.4	26: .30	Instr	Scan	5: .14	22: .30	Instr	Scan	10: .04
532.2	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .22
532.6	5: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
533.6	5: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
534.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
578.6	1:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	1: .10
578.8	26: .30	Instr	Scan	4: .04	22: .30	Instr	Scan	1: .14

Figure 5.2 (cont.)

579.6	4: .42	Instr	Scan	26: .30	1: .32	Audio	SBsys	22: .30
579.8	4: .42	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
580.2	4: .42	Instr	H	26: .30	22: .30	Instr	Scan	0: .00
580.6	4: .42	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
581.6	24: .82	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
583.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
589.6	3: .31	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
590.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
596.0	26: .30	Instr	Scan	4: .27	1: .32	Audio	SBsys	22: .30
596.2	4: .45	Instr	Scan	26: .30	22: .30	Instr	Scan	16: .04
597.4	4: .45	Instr	Scan	26: .30	16: .32	SBsys	SBsys	22: .30
598.2	26: .30	Instr	Scan	0: .00	16: .32	SBsys	SBsys	22: .30
601.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
606.2	1: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
606.4	26: .30	Instr	Scan	20: .10	22: .30	Instr	Scan	10: .04
607.4	20: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	10: .27
607.6	20: .32	Instr	Scan	26: .30	10: .32	SBsys	SBsys	22: .30
608.6	20: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
609.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
616.8	4: .60	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
618.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
626.8	4: .59	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
627.0	4: .59	Instr	V	26: .30	22: .30	Instr	Scan	0: .00
627.2	4: .59	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
628.8	6: .75	SBsys	SBsys	26: .30	22: .30	Instr	Scan	0: .00
630.0	6: .75	SBsys	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
630.2	6: .75	SBsys	SBsys	26: .30	22: .30	Instr	Scan	8: .04
630.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	8: .17
631.4	26: .30	Instr	Scan	0: .00	8: .32	Instr	V	22: .30
631.6	26: .30	Instr	Scan	0: .00	8: .32	SBsys	SBsys	22: .30
635.4	26: .30	Instr	Scan	1: .10	1:1.00	Audio	SBsys	22: .30
635.6	26: .30	Instr	Scan	1: .14	22: .30	Instr	Scan	2: .04
636.4	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	2: .22
636.6	26: .30	Instr	Scan	19: .10	22: .30	Instr	Scan	2: .27
636.8	26: .30	Instr	Scan	19: .14	2: .32	SBsys	SBsys	22: .30
637.6	19: .32	Instr	Scan	26: .30	2: .32	SBsys	SBsys	22: .30
637.8	19: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
639.6	1: .78	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
639.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
653.8	26: .30	Instr	Scan	1: .10	1:1.00	Audio	SBsys	22: .30
654.0	26: .30	Instr	Scan	1: .14	22: .30	Instr	Scan	3: .04
654.8	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	3: .22
655.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	3: .27
655.2	26: .30	Instr	Scan	0: .00	3: .32	SBsys	SBsys	22: .30
656.2	26: .30	Instr	Scan	1: .27	22: .30	Instr	Scan	0: .00
656.4	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
656.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
692.0	4: .36	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
693.0	4: .36	Instr	Psi	26: .30	22: .30	Instr	Scan	0: .00
693.4	4: .36	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
694.0	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
704.8	16: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00

Figure 5.2 (cont.)

706.0	16: .32	Audio	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
706.2	16: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	9: .04
706.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	9: .17
707.4	26: .30	Instr	Scan	0: .00	9: .32	SBsys	SBsys	22: .30
708.8	1: .32	Audio	SBsys	26: .30	9: .32	SBsys	SBsys	22: .30
709.0	26: .30	Instr	Scan	7: .04	9: .32	SBsys	SBsys	22: .30
710.2	7: .32	SBsys	SBsys	26: .30	9: .32	SBsys	SBsys	22: .30
711.4	7: .32	SBsys	SBsys	26: .30	22: .30	Instr	Scan	0: .00
712.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
726.4	21: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
728.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
736.2	4: .39	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
736.4	4: .39	Instr	V	26: .30	22: .30	Instr	Scan	0: .00
736.6	4: .39	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
738.2	6: .79	SBsys	SBsys	26: .30	22: .30	Instr	Scan	0: .00
739.4	6: .79	SBsys	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
739.6	6: .79	SBsys	SBsys	26: .30	22: .30	Instr	Scan	8: .04
740.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	8: .17
740.8	26: .30	Instr	Scan	0: .00	8: .32	Instr	V	22: .30
741.0	26: .30	Instr	Scan	0: .00	8: .32	SBsys	SBsys	22: .30
744.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
746.4	22: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
747.4	22: .32	Instr	V	26: .30	22: .30	Instr	Scan	0: .00
747.6	22: .32	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
748.4	6: .78	SBsys	SBsys	26: .30	22: .30	Instr	Scan	0: .00
749.6	6: .78	SBsys	SBsys	26: .30	1: .32	Audio	SBsys	22: .30
749.8	6: .78	SBsys	SBsys	26: .30	22: .30	Instr	Scan	8: .04
750.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	8: .17
751.0	26: .30	Instr	Scan	0: .00	8: .32	Instr	V	22: .30
751.2	26: .30	Instr	Scan	0: .00	8: .32	SBsys	SBsys	22: .30
755.0	26: .30	Instr	Scan	0: .00	1:1.00	Audio	SBsys	22: .30
755.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	18: .04
756.4	26: .30	Instr	Scan	0: .00	18: .32	SBsys	SBsys	22: .30
760.4	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
762.2	17:1.00	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
764.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
786.6	26: .30	Instr	Scan	0: .00	1: .32	Audio	SBsys	22: .30
786.8	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	19: .04
788.0	26: .30	Instr	Scan	0: .00	19: .32	SBsys	SBsys	22: .30
790.6	4: .41	Instr	Scan	26: .30	19: .32	SBsys	SBsys	22: .30
792.0	4: .41	Instr	Scan	26: .30	22: .30	Instr	Scan	0: .00
794.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
827.4	1:1.00	Audio	SBsys	26: .30	1:1.00	Audio	SBsys	22: .30
827.6	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	4: .04
828.8	26: .30	Instr	Scan	0: .00	4: .32	SBsys	SBsys	22: .30
829.8	26: .30	Instr	Scan	1: .27	22: .30	Instr	Scan	0: .00
830.0	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
830.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
866.8	26: .30	Instr	Scan	0: .00	23: .32	Instr	H	22: .30
870.6	26: .30	Instr	Scan	0: .00	23:1.00	Audio	SBsys	22: .30
871.8	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
872.0	27:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00

Figure 5.2 (cont.)

872.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
915.4	26: .30	Instr	Scan	0: .00	24: .33	Instr	H	22: .30
919.6	26: .30	Instr	Scan	0: .00	24:1.00	Audio	SBsys	22: .30
920.8	1: .32	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
921.0	27:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
921.2	26: .30	Instr	Scan	0: .00	22: .30	Instr	Scan	0: .00
935.2	26: .30	Instr	Scan	0: .00	25: .37	Instr	H	22: .30
938.6	26: .30	Instr	Scan	0: .00	25:1.00	Audio	SBsys	22: .30
939.8	1: .32	Audio	SBsys	26: .30	6: .55	SBsys	SBsys	22: .30
940.0	27:1.00	Audio	SBsys	26: .30	6: .55	SBsys	SBsys	22: .30
940.2	26: .30	Instr	Scan	0: .00	6: .55	SBsys	SBsys	22: .30
942.6	26: .30	Instr	Scan	0: .00	6: .55	Extnl	Scan	22: .30
945.2	26: .30	Instr	Scan	0: .00	6: .55	SBsys	SBsys	22: .30
945.4	1:1.00	Audio	SBsys	26: .30	6: .55	SBsys	SBsys	22: .30
945.6	26: .30	Instr	Scan	1: .10	6: .55	SBsys	SBsys	22: .30
946.6	1: .32	Audio	SBsys	26: .30	6: .55	SBsys	SBsys	22: .30
946.8	8:1.00	SBsys	SBsys	26: .30	6: .55	SBsys	SBsys	22: .30
948.2	8:1.00	SBsys	SBsys	26: .30	6: .55	Instr	Scan	22: .30
948.4	8:1.00	SBsys	SBsys	26: .30	1:1.00	Audio	SBsys	26:1.00
948.6	8:1.00	SBsys	SBsys	26: .30	26:1.00	Audio	SBsys	22: .30
949.8	8:1.00	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
950.0	1: .37	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
950.2	27:1.00	Audio	SBsys	26: .30	22: .30	Instr	Scan	0: .00
950.4	26: .30	Extnl	Scan	0: .00	22: .30	Instr	Scan	0: .00
954.0	23: .33	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
956.0	26: .30	Extnl	Scan	0: .00	22: .30	Instr	Scan	0: .00
963.6	4: .39	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
964.4	4: .39	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
964.8	4: .39	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
965.6	18: .75	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00
967.6	26: .30	Extnl	Scan	0: .00	22: .30	Instr	Scan	0: .00
974.6	4: .34	Extnl	Scan	26: .30	22: .30	Instr	Scan	0: .00

crew member, the gain for doing that procedure (EGP) and the information cluster and display being attended to at a given time. Also provided for each crew member is the procedure that has the next highest gain for execution at that time. Procedure numbers used in the PTL correspond to those in Table 4.20. Thus, for example, at time 915.4 seconds, PF was flying on instruments (scanning) and no other procedures were competing for attention. At the same time, PNF was monitoring the altimeter in order to make an altitude callout (at t=919.6), while the default monitoring task was the task with the next highest priority. Shortly thereafter (920.8 sec), PF diverts attention from regulating about the nominal to process the callout and PNF has reverted to basic monitoring.

The message time line (MTL) is a record of all the communication traffic and auditory signals that occur in the simulated cockpit. Figure 5.3 is a message time line for the nominal approach. The type of message (Signal name), the source of the message and its destination, its processing status, its time of origin and processing, as well as an indication of the signal content are all presented using mnemonics that are fairly transparent. For example, on the message time line, we see the communication activity noted above. The 500′ altitude callout is made by the F/O (PNF) at 919.6 seconds and directed to the CAPT (PF). It is processed (i.e. used to update PF′s altitude estimate) at 921.0 seconds.

Figure 5.3: Sample PROCRU Message Time-Line (case 1LS)

SIGNL NAME	SOURC CODE	DESTN CODE	PROCS STATs	TIME ORIGN	TIME PROCs	SIGNL CONTs
Turn	A.T.C	Capt.	Prcsd	0.0	2.2	270.
Turn	A.T.C	FO	Prcsd	0.0	2.6	270.
ATCcn	FO	A.T.C	Ignrd	3.4	3.6	
Decel	A.T.C	Capt.	Prcsd	30.0	32.2	170.
Decel	A.T.C	FO	Prcsd	30.0	32.6	170.
ATCcn	FO	A.T.C	Ignrd	33.4	33.6	
ChAlt	A.T.C	Capt.	Prcsd	50.0	54.0	3500.
ChAlt	A.T.C	FO	Prcsd	50.0	52.6	3500.
ATCcn	FO	A.T.C	Ignrd	53.4	53.6	
AAon	Capt.	Annoc	Ignrd	57.8	58.0	3500.
AltAl	SBsys	Capt.	Prcsd	269.2	270.8	3500.
AltAl	SBsys	FO	Ignrd	269.2	270.4	3500.
AAoff	Capt.	Annoc	Ignrd	270.8	271.0	
IACR	Capt.	SO	Prcsd	294.2	294.4	
IACst	SO	Annoc	Ignrd	294.4	294.6	
Decel	A.T.C	Capt.	Prcsd	310.0	312.2	160.
Decel	A.T.C	FO	Prcsd	310.0	312.6	160.
ATCcn	FO	A.T.C	Ignrd	313.4	313.6	
IAC#1	SO	FO	Prcsd	314.4	317.0	
IAC#1	FO	SO	Prcsd	320.8	321.0	
FlapR	Capt.	FO	Prcsd	324.0	326.6	5.
FlapS	FO	Annoc	Ignrd	326.6	326.8	5.
IAC#2	SO	FO	Prcsd	341.0	343.6	
IAC#2	FO	SO	Prcsd	347.4	347.6	
IAC#3	SO	FO	Prcsd	367.6	370.2	
IAC#3	FO	SO	Prcsd	374.0	374.2	
IAC#4	SO	FO	Prcsd	394.2	396.8	
IAC#4	FO	SO	Prcsd	400.6	400.8	
IAC#5	SO	FO	Prcsd	420.8	423.4	
IAC#5	FO	SO	Prcsd	427.2	427.4	
Turn	A.T.C	Capt.	Prcsd	440.0	442.2	180.
Turn	A.T.C	FO	Prcsd	440.0	442.6	180.
ATCcn	FO	A.T.C	Ignrd	443.4	443.6	
IACfn	SO	Annoc	Ignrd	447.4	447.6	
ChAlt	A.T.C	Capt.	Prcsd	480.0	482.2	2000.
ChAlt	A.T.C	FO	Prcsd	480.0	482.6	2000.
ATCcn	FO	A.T.C	Ignrd	483.4	483.6	
AAon	Capt.	Annoc	Ignrd	486.0	486.2	2000.
Turn	A.T.C	Capt.	Prcsd	530.0	532.2	120.
Turn	A.T.C	FO	Prcsd	530.0	532.6	120.
ATCcn	FO	A.T.C	Ignrd	533.4	533.6	
AltAl	SBsys	Capt.	Prcsd	578.4	581.6	2000.
AltAl	SBsys	FO	Ignrd	578.4	579.6	2000.
AAoff	Capt.	Annoc	Ignrd	581.6	581.8	
FACR	Capt.	SO	Prcsd	589.6	589.8	
FACst	SO	Annoc	Ignrd	589.8	590.0	
FAC#1	SO	FO	Prcsd	594.8	597.4	
FAC#1	FO	SO	Prcsd	601.2	601.4	
ClrFL	A.T.C	Capt.	Prcsd	605.0	606.2	

Figure 5.3 (cont.)

ClrFL	A.T.C	FO	Prcsd	605.0	607.6	
ATCcn	FO	A.T.C	Ignrd	608.4	608.6	
FlapR	Capt.	FO	Prcsd	628.8	631.4	15.
FlapS	FO	Annoc	Ignrd	631.4	631.6	15.
LOCon	SBsys	Capt.	Prcsd	635.2	636.4	
LOCon	SBsys	FO	Prcsd	635.2	635.4	
Loc A	FO	Capt.	Ignrd	636.8	639.6	
GSon	SBsys	Capt.	Prcsd	653.6	654.8	
GSon	SBsys	FO	Prcsd	653.6	653.8	
GslpA	FO	Capt.	Ignrd	655.2	656.4	
GearR	Capt.	FO	Prcsd	704.8	707.4	1.
GearD	FO	Annoc	Ignrd	707.4	707.6	
FAC#2	SO	Capt.	Prcsd	707.6	710.2	
FAC#2	Capt.	SO	Prcsd	712.0	712.2	
FlapR	Capt.	FO	Prcsd	738.2	740.8	25.
FlapS	FO	Annoc	Ignrd	740.8	741.0	25.
FlapR	Capt.	FO	Prcsd	748.4	751.0	30.
FlapS	FO	Annoc	Ignrd	751.0	751.2	30.
FAC#3	SO	FO	Prcsd	751.2	756.4	
FAC#3	FO	SO	Prcsd	760.2	760.4	
FAC#6	SO	FO	Prcsd	785.4	788.0	
FAC#6	FO	SO	Prcsd	791.8	792.0	
FACfn	SO	Annoc	Ignrd	797.0	797.2	
OMon	SBsys	Capt.	Prcsd	827.2	827.4	
OMon	SBsys	FO	Prcsd	827.2	827.4	
OMann	FO	Capt.	Ignrd	828.8	830.0	
AltCo	FO	Capt.	Prcsd	870.6	872.0	1000.
AltCo	FO	Capt.	Prcsd	919.6	921.0	500.
AltCo	FO	Capt.	Prcsd	938.6	940.0	300.
MMon	SBsys	Capt.	Prcsd	945.2	945.4	
MMon	SBsys	FO	Prcsd	945.2	948.4	
RwisC	FO	Capt.	Prcsd	945.2	946.8	
AltCo	FO	Capt.	Prcsd	948.6	950.2	200.

The milestone time line (TL) is an approximation to the time line used in Chapter 2. It contains selected trajectory variables of interest (altitude, speed and heading), an indication of crew activity and a listing of important flight milestones and events. The milestone time line for the nominal approach is given in Figure 5.4; and this can be directly compared with the time line in Chapter 2. Note that the time marker given in the TL, t_{go}, is the time-to-go, computed simply as 980s minus the event time. This provides a fair approximation to the actual time-to-go.

5.3 Simulation Results

Table 5.3 is a list of the cases simulated here with PROCRU. The designations L and H refer to the ATC scenario (low and high workload) while the S and M refer to SAP and MAP. Case 1LS is the nominal approach, i.e., nominal in terms of both scenario and PROCRU model parameters. The other cases correspond to variations in approach conditions and model parameters.

In discussing the results from these cases we must note that a single sample of the random disturbances has been used throughout, to facilitate comparison without resorting to Monte Carlo simulation. Thus, one should not draw any definitive conclusions with respect to performance or procedures from these results.

Table 5.3: PROCRU Simulated Cases

Case No.	App. Scen.	Disturbance	Attention	Lock-Up Times	Default Gain (PF/PNF)	Procedure
1LS	ATCLO	Low	Full	Base	Base	SAP
1LM	ATCLO	Low	Full	Base	Base	MAP
2LS	ATCLO	High	Full	Base	Base	SAP
3LS	ATCLO	Low	One-Half	Base	Base	SAP
4LS	ATCLO	High	One-Half	Base	Base	SAP
4LM	ATCLO	High	One-Half	Base	Base	MAP
5LS	ATCLO	Low	Full	1.5xBase	Base	SAP
6LS	ATCLO	Low	Full	Base	2xBase	SAP
1HS	ATCHI	Low	Full	Base	Base	SAP
1HM	ATCHI	Low	Full	Base	Base	MAP
4HS	ATCHI	High	One-Half	Base	Base	SAP
4HM	ATCHI	High	One-Half	Base	Base	MAP

5.3.1 Nominal Approach (SAP)

The milestone time line in Figure 5.4 presents an overview of crew activity for the nominal case and will be discussed in detail.

The time-line begins with the vehicle at 10,000 ft altitude, on a 210 deg heading, proceeding at 190 kts. In the first 50 seconds, three ATC requests, for a heading change, deceleration, and descent, are processed by both the PF and PNF. As shown in both Figure 5.4 and Figure 5.3, each request involves: a) a message generated by ATC (occurring at the time specified by Table 5.1), sent to both the PF and PNF; b) message processing by the PF, resulting in a new maneuver (e.g., "Prcsd Turn"); and c) message processing by the PNF, resulting in a verbal confirmation of the ATC request (e.g., "ATCcn"). Note that Figure 5.3 shows that each confirmation message (from PNF to ATC) is ignored by ATC, since the ATC module used in this simulation operates in a time-locked open-loop fashion. Naturally, a more sophisticated module would take into account the procedural activity of ATC, and incorporate the verbal confirmatory feedback provided by the crew.

The descent request made by ATC at t_{go} = 930s triggers a number of crew activities. As just noted, it triggers a verbal confirmation by the PNF. It also triggers the generation of a three-segment maneuver (flare/descent/flare) by the PF, in

Figure 5.4: Sample PROCRU Milestone Time-Line (Case 1LS)

TIME	VEHICLE STATE			CREW ACTIVITY			FLIGHT MILESTONES
TGo	Alt	Vel	Head	Captain (PF)	FOfficer (PNF)	SOfficer	
							ATC:TURN to 270. deg
980.0	10000	190	210				
							End S & L Begin TURN to 270.0 deg
				PrcsdTurn			
977.8	10000	189	210				
					PrcsdTurn		
977.4	9999	189	211				
					ATCcn		
976.6	9999	190	213				
							End TURN Begin S & L
957.8	10000	190	270				
							ATC:DECELto 170. kts
950.0	10002	189	270				
							End S & L Begin DECEL to 170.0 kts
				PrcsdDecel			
947.8	10003	189	270				
					PrcsdDecel		
947.4	10003	189	270				
					ATCcn		
946.6	10004	188	270				
							ATC:DSCNDto3500. ft
930.0	10001	172	270				
							End DECEL Begin S & L
927.6	10001	170	270				
					PrcsdChAlt		
927.4	10001	170	270				
					ATCcn		
926.6	10001	170	270				
							End S & L Begin FLARE to -6.0 deg
				PrcsdChAlt			
926.0	10001	170	270				
				AAon			
922.2	9995	170	270				
							End FLARE Begin DSCNT to 3947.0 ft
895.6	9541	170	270				
							AA active
710.8	4019	170	270				
				AAoff PrcsdAltAl			
709.2	3972	170	270				
							AA inactive
709.0	3966	170	269				

Figure 5.4 (cont.)

							End DSCNT Begin FLARE to 0.0 deg
707.2	3912	170	269				
				IACR			
685.8	3500	170	269				
						IACst PrcsdIACR	
685.6	3498	170	269				
							End FLARE Begin S & L
676.6	3466	169	269				
							ATC:DECELto 160. kts
670.0	3465	170	269				
							End S & L Begin DECEL to 160.0 kts
				PrcsdDecel			
667.8	3465	170	269				
					PrcsdDecel		
667.4	3465	169	269				
					ATCcn		
666.6	3465	168	269				
						IAC#1	
665.6	3465	167	269				
					PrcsdIAC#1		
663.0	3465	165	269				
					IAC#1		
659.2	3465	161	269				
						PrcsdIAC#1	
659.0	3465	161	269				
							End DECEL Begin S & L
657.6	3465	159	269				
				FlapR			
656.0	3466	159	269				
							Flaps at 5.0
					FlapS PrcsdFlapR		
653.4	3467	159	270				
						IAC#2	
639.0	3464	160	270				
					PrcsdIAC#2		
636.4	3464	160	269				
					IAC#2		
632.6	3465	159	269				
						PrcsdIAC#2	
632.4	3465	159	269				
						IAC#3	
612.4	3467	159	269				
					PrcsdIAC#3		
609.8	3467	159	269				
					IAC#3		
606.0	3467	159	269				
						PrcsdIAC#3	
605.8	3467	159	269				
						IAC#4	
585.8	3463	160	270				

Figure 5.4 (cont.)

					PrcsdIAC#4		
583.2	3463	160	270				
					IAC#4		
579.4	3463	160	270				
						PrcsdIAC#4	
579.2	3463	160	270				
						IAC#5	
559.2	3465	159	270				
					PrcsdIAC#5		
556.6	3464	159	269				
					IAC#5		
552.8	3463	160	270				
						PrcsdIAC#5	
552.6	3463	160	270				
							ATC:TURN to 180. deg
540.0	3462	160	270				
							End S & L Begin TURN to 180.0 deg
				PrcsdTurn			
537.8	3463	160	270				
					PrcsdTurn		
537.4	3463	160	268				
					ATCcn		
536.6	3464	159	266				
						IACfn	
532.6	3464	160	254				
							End TURN Begin S & L
507.8	3464	160	180				
							ATC:DSCNDto2000. ft
500.0	3465	159	180				
							End S & L Begin FLARE to -3.2 deg
				PrcsdChAlt			
497.8	3465	159	180				
					PrcsdChAlt		
497.4	3465	159	180				
					ATCcn		
496.6	3464	159	180				
				AAon			
494.0	3457	160	180				
							End FLARE Begin DSCNT to 2118.5 ft
481.2	3334	160	180				
							ATC:TURN to 120. deg
450.0	2866	159	179				
				PrcsdTurn			
447.8	2834	159	179				
					PrcsdTurn		
447.4	2828	159	179				
					ATCcn		
446.6	2815	159	179				

Figure 5.4 (cont.)

							AA active
401.6	2138	159	179				
							End DSCNT Begin FLARE to 0.0 deg
399.4	2105	159	179				
				AAoff PrcsdAltAl			
398.4	2091	159	179				
							AA inactive
398.2	2086	159	179				
				FACR			
390.4	2008	159	179				
						FACst PrcsdFACR	
390.2	2007	159	179				
						FAC#1	
385.2	1988	159	180				
							End FLARE Begin TURN to 120.0 deg
383.0	1987	159	180				
					PrcsdFAC#1		
382.6	1987	159	178				
					FAC#1		
378.8	1987	159	167				
						PrcsdFAC#1	
378.6	1987	159	167				
							ATC:Cleared to land
375.0	1988	159	156				
				PrcsdClrFL			
373.8	1989	159	152				
					PrcsdClrFL		
372.4	1989	159	148				
					ATCon		
371.6	1990	159	146				
							End TURN Begin DECEL to 150.0 kts
363.0	1986	159	120				
							End DECEL Begin S & L
352.8	1988	149	120				
				FlapR			
351.2	1988	149	120				
							Flaps at 15.0
					FlapS PrcsdFlapR		
348.6	1985	149	120				
							LOC: on -2.5 dots
344.8	1981	149	120				
					PrcsdLOCon		
344.6	1981	149	120				
				PrcsdLOCon			
343.6	1980	149	120				

Figure 5.4 (cont.)

					Loc A		
343.2	1980	149	120				
							End S & L Begin TURN to 90.0 deg
342.4	1979	149	120				
							GS: on -2.9 dots
326.4	1975	150	111				
					PrcsdGSon		
326.2	1975	150	111				
				PrcsdGSon			
325.2	1975	150	110				
					GslpA		
324.8	1975	150	110				
							End TURN Begin S & L
286.6	1978	150	89				
				GearR			
275.2	1977	150	90				
							Landing gear down
					GearD PrcsdGearR		
272.6	1977	150	90				
						FAC#2	
272.4	1977	150	90				
				PrcsdFAC#2			
269.8	1978	150	90				
				FAC#2			
268.0	1979	150	90				
						PrcsdFAC#2	
267.8	1979	150	90				
							End S & L Begin DECEL to 140.0 kts
253.6	1980	149	90				
							End DECEL Begin S & L
243.4	1979	139	90				
				FlapR			
241.8	1978	139	90				
							Flaps at 25.0
					FlapS PrcsdFlapR		
239.2	1976	140	90				
							End S & L Begi DECEL to 139.0 kts
233.6	1976	140	90				
							End DECEL Begin S & L
232.4	1976	138	90				
				FlapR			
231.6	1976	138	90				
							Flaps at 30.0
					FlapS PrcsdFlapR		
229.0	1976	138	90				
						FAC#3	
228.8	1976	138	90				

Figure 5.4 (cont.)

```
                                          PrcsdFAC#3
223.6  1976 138  89
                                          FAC#3
219.8  1976 138  89
                                                   PrcsdFAC#3
219.6  1976 138  89
                                                         End S & L Begin FLARE
                                                         to   -2.5  deg
217.8  1976 138  89
                                                   FAC#6
194.6  1881 138  90
                                          PrcsdFAC#6
192.0  1858 138  90
                                          FAC#6
188.2  1821 138  90
                                                   PrcsdFAC#6
188.0  1819 138  90
                                                         End FLARE Begin DSCNT
187.4  1813 138  90
                                                   FACfn
183.0  1766 139  90
                                                         OM active
152.8  1458 139  89
                                 PrcsdOMon
                                          PrcsdOMon
152.6  1456 139  89
                                          OMann
151.2  1443 139  89
                                                         OM inactive
150.6  1437 139  89
                                          AltCo
109.4  1016 139  90
                                 PrcsdAltCo
108.0  1002 139  90
                                          AltCo
 60.4   510 139  90
                                 PrcsdAltCo
 59.0   497 139  90
                                          AltCo
 41.4   315 139  89
                                 PrcsdAltCo
 40.0   300 139  89
                                                         MM Active
                                          RwisC
 34.8   248 139  89
                                 PrcsdMMon
 34.6   246 139  89
                                 PrcsdRwisC
 33.2   233 138  90
                                          PrcsdMMon
 31.6   217 138  90
                                          AltCo
 31.4   215 138  90
```

Figure 5.4 (cont.)

					MM inactive
30.4	205	138	90	PrcsdAltCo	
29.8	199	138	90		End DSCNT Begin DECEL to 134.0 kts
26.0	160	138	90		End DECEL Begin DSCNT
15.2	49	133	89		End DSCNT Begin FLARE to 0.0 deg
14.4	41	133	89		GS off
12.0	20	133	90		LOC off
8.2	0	133	89		

accordance with the procedure outlined in Table 4.6. Thus, a flare to -6 deg flight path is initiated at t_{go} = 926s, and constant sink rate is maintained until t_{go} = 707s, at which point a flare-out is initiated, and completed at t_{go} = 676s. The ATC descent request also triggers an altitude alert setting by the PF ("AAon" at t_{go} = 922s), in accordance with the procedure outlined in Table 4.15.

As the vehicle approaches the requested 3500 ft altitude, the PF makes a verbal request for the initial approach checklist ("IACR" at t_{go} = 686s) which, as shown by Figure 5.3, is processed by the S/O at t = 294s. This then initiates the series of IAC prompts by the S/O, shown in the next few minutes of the time-line. Each such prompt (e.g., "IAC #1" at t_{go} = 666s) results in a requirement on the PF or PNF to process that prompt (e.g., "Procsd IAC 1" at t_{go} = 663s), and verbally echo the prompt back to the S/O. Subsequent processing of the confirmation by the S/O (e.g., "Prcsd IAC #1" at t_{go} = 659s), initiates generation of another prompt by the S/O (e.g., "IAC #2" at t_{go} = 639s). The IAC is concluded at t_{go} = 533s by a "IACfn" message generated by the S/O.

The descent to 3500 ft also triggers the altitude alert (AA) subsystem. Thus, at h = 4019 ft the AA becomes active, which requires the PF to turn it off at t_{go} = 709s, which, in turn deactivates the AA at the next time step in the simulation. Note that this occurs prior to the flare-out initiated by the PF, thus providing an appropriate warning to begin the flare-out.

After the PF levels off near the requested 3500 ft altitude, ATC requests a deceleration to 160 kt. As before, this triggers a maneuver by the PF and a message confirmation by the PNF. Note that completion of this maneuver triggers a 5 deg flap request by the PF (t_{go} = 656), in accordance with the flap/speed management procedure outlined in Table 4.11.

Following an ATC-requested turn to 180 deg (t_{go} = 540s), a second descent to 2000 ft is initiated (t_{go} = 498s). The same activity sequence is followed as in the first descent, except that ATC makes a 120 deg turn request (t_{go} = 450s) while the vehicle is descending. The message is processed by both crew members (as shown in Figure 5.3), and confirmation is provided by the PNF. The PF, however, does not act on this request, but merely stores it in his memory. Once he levels off to the requested 2000 ft altitude (t_{go} = 383s), he then immediately initiates the turn to 120 deg.

As in the initial descent, the PF requests the checklist during his levelling off to his assigned altitude ("FACR" at t_{go} = 390s). Again, this initiates a series of S/O prompts and PF and PNF confirmations, lasting until checklist termination by the S/O ("FACfn" at t_{go} = 183s).

While the PF is turning to the requested 120 deg heading, ATC notifies the crew that they are cleared to land (t_{go} = 375s). This

message is processed by both the PF and PNF, and "enables" a series of velocity, altitude, and heading management procedures designed to ensure proper touchdown performance.

The first of these is a deceleration to 150 kt, following completion of the turn to 120 deg (t_{go} = 363s). Once this speed is reached, 15 deg flaps are requested and set, by the PF and PNF respectively (t_{go} = 349s). Shortly thereafter, the localizer becomes active, which results in an announcement by the PNF, which, in turn, triggers a turn to final by the PF.

During the turn, the glide slope becomes active (t_{go} = 326s), and is announced by the PNF. After the turn is completed, the vehicle has achieved its final inbound heading, with a small localizer error (not shown on the time-line). Shortly thereafter, a 2 dot low glide slope error (also not shown), triggers a gear-down request from the PF, which is acted on by the PNF (t_{go} = 273s).

As the vehicle approaches the glide slope, the PF initiates two decelerations in accordance with the velocity maneuver procedures of Table 4.3: one to 140 kt at 1.5 dots low, and the second to the final approach speed of 139 kt, at 1 dot low. Each of these trigger new flap requests and settings (to 25 and 30 deg) in accordance with the flap/speed management procedure of Table 4.11.

When the vehicle is 0.5 dots below the glide slope, the PF initiates a pitch down (t_{go} = 218s). This flare sets up the final descent followed for the remainder of the approach.

During the descent, the PNF announces OM activity ("OMann" at t_{go} = 151s), and makes the required 1000 ft, 500 ft, and "approaching minimum"s (300 ft) callouts. He is also monitoring out-the-window, and, with the 250 ft ceiling simulated, makes the appropriate RWIS callout at t_{go} = 35s.

While the PNF is monitoring for this RWIS callout, the MM alert sounds, and both pilots process this message. The PNF should announce MM activity during this time, but is engaged in monitoring the altimeter for his required "minimums" callout at 200 ft. He makes the altitude callout slightly early (at h=215ft and t_{go} = 31s), and by the time he can attend to making the MM announcement, the MM becomes inactive (at t_{go} = 30s). Since the announcement procedure, as programmed, requires the MM to be active for an announcement to be made, the PNF remains silent.

The PF begins decelerating to the required threshold speed of 134 kt slightly early (at t_{go} = 26s) and 10 ft above the 150 ft altitude specified in Table 4.3. The final flare is initiated about 1 sec late and 10 ft below the 50 ft altitude specified in Table 4.5. During this flare the GS signal turns off because of

the flare away from the glide slope beam, and the LOC signal turns off at touchdown, as required by the LOC characteristics modelled in this simulation (see Appendix B).

5.3.2 Monitored Approach (MAP)

Since the monitored approach procedure (MAP) differs from the standard approach procedure (SAP) only in the last few hundred feet of the approach, we show only the last half-minute of the MAP time-line in Figure 5.5. The assumption here is that, during the early portion of the approach, the CAPT is the PNF, and the F/O the PF. Thus, the MAP milestone time-line for events earlier than those shown in Figure 5.5 would be identical to those shown for the SAP in Figure 5.4, with the flying duties of the CAPT and F/O reversed.

The time-line of Figure 5.5 begins with a RWIS recognition by the CAPT (near the ceiling altitude of 250 ft), and subsequent control transfer. As in the SAP time-line, the requirement to make the 200 ft altitude callout causes the PNF (now the F/O) to miss the announcement of MM activity. The remainder of the descent, flare, and touchdown closely parallels that of the SAP shown earlier.

Figure 5.5: Monitored Approach Time-Line (case 1LS)

TIME	VEHICLE STATE			CREW ACTIVITY			FLIGHT MILESTONES
TGo	Alt	Vel	Head	Captain	FOfficer	SOfficer	
					. . . (See timeline for SAP) . . .		
				"Takeover"	"Relinquish"		MAP: Control swap
				PrcsdMMon			
					PrcsdMMon		
34.4	244	139	90				
					AltCo		
30.6	206	138	90				
							MM inactive
30.4	204	138	90				
				PrcsdAltCo			
29.2	192	138	90				
							End DSCNT Begin DECEL to 134.0 kts
26.2	161	138	90				
							End DECEL Begin DSCNT
15.4	52	133	89				
							End DSCNT Begin FLARE to 0.0 deg
14.6	44	133	89				
							GS off
12.6	27	133	89				
							LOC off
6.0	0	133	90				

5.3.3 High Workload Approach (SAP/ATCHI)

Figure 5.6 shows the milestone time-line corresponding to the high workload approach scenario (ATCHI) conducted under standard approach procedures. The ATC commands associated with this scenario are given in Table 5.1.

A comparison with the nominal workload approach points out a number of interesting differences in procedural activity. We discuss a few of these differences in the following paragraphs.

Figure 5.6 shows the high workload procedural activity to be identical to that of the nominal approach of Figure 5.4 up until t_{go} = 615s, when the early ATC turn request is made. The PF's response is to initiate the turn (at t_{go} = 613s) and the PNF's response is to confirm the request (at t_{go} = 612s). A comparison with the nominal case shows that this requires the PNF to interleave this confirmation with a checklist verification ("IAC #3" in response at t_{go} = 606) to the S/O's prompt.

While the F/O and S/O continue the IAC, the PF finishes the turn to the new 180 deg heading, and, in response to the accelerated ATC descent request (t_{go} = 575s), begins the flare to achieve the desired sink rate. Shortly thereafter (t_{go} = 533s), the S/O completes the IAC. A comparison with the nominal approach time-line shows the IAC completed during the turn to 180 deg, and prior to the descent maneuver. Thus, in the high workload

Figure 5.6: Milestone Time-Line: High ATC Workload Scenario (case 1LS)

TIME TGo	VEHICLE STATE Alt	Vel	Head	CREW ACTIVITY Captain (PF)	FOfficer (PNF)	SOfficer	FLIGHT MILESTONES
							ATC:TURN to 270. deg
980.0	10000	190	210				
							End S & L Begin TURN to 270.0 deg
				PrcsdTurn			
977.8	10000	189	210				
					PrcsdTurn		
977.4	9999	189	211				
					ATCcn		
976.6	9999	190	213				
							End TURN Begin S & L
957.8	10000	190	270				
							ATC:DECELto 170. kts
950.0	10002	189	270				
							End S & L Begin DECEL to 170.0 kts
				PrcsdDecel			
947.8	10003	189	270				
					PrcsdDecel		
947.4	10003	189	270				
					ATCcn		
946.6	10004	188	270				
							ATC:DSCNDto3500. ft
930.0	10001	172	270				
							End DECEL Begin S & L
927.6	10001	170	270				
					PrcsdChAlt		
927.4	10001	170	270				
					ATCcn		
926.6	10001	170	270				
							End S & L Begin FLARE to -6.0 deg
				PrcsdChAlt			
926.0	10001	170	270				
				AAon			
922.2	9995	170	270				
							End FLARE Begin DSCNT to 3947.0 ft
895.6	9541	170	270				
							AA active
710.8	4019	170	270				
				AAoff PrcsdAltAl			
709.2	3972	170	270				
							AA inactive
709.0	3966	170	269				

Figure 5.6 (cont.)

							End DSCNT Begin FLARE to 0.0 deg
707.2	3912	170	269				
				IACR			
685.8	3500	170	269				
						IACst PrcsdIACR	
685.6	3498	170	269				
							End FLARE Begin S & L
676.6	3466	169	269				
							ATC:DECELto 160. kts
670.0	3465	170	269				
							End S & L Begin DECEL to 160.0 kts
				PrcsdDecel			
667.8	3465	170	269				
					PrcsdDecel		
667.4	3465	169	269				
					ATCcn		
666.6	3465	168	269				
						IAC#1	
665.6	3465	167	269				
					PrcsdIAC#1		
663.0	3465	165	269				
					IAC#1		
659.2	3465	161	269				
						PrcsdIAC#1	
659.0	3465	161	269				
							End DECEL Begin S & L
657.6	3465	159	269				
				FlapR			
656.0	3466	159	269				
							Flaps at 5.0
					FlapS PrcsdFlapR		
653.4	3467	159	270				
						IAC#2	
639.0	3464	160	270				
					PrcsdIAC#2		
636.4	3464	160	269				
					IAC#2		
632.6	3465	159	269				
						PrcsdIAC#2	
632.4	3465	159	269				
							ATC:TURN to 180. deg
615.0	3467	159	269				
							End S & L Begin TURN to 180.0 deg
				PrcsdTurn			
612.8	3467	159	269				

Figure 5.6 (cont.)

IAC#3

PrcsdTurn

612.4 3467 159 268

ATCcn

611.6 3467 159 266

PrcsdIAC#3

609.8 3466 160 261

IAC#3

606.0 3465 159 249

PrcsdIAC#3

605.8 3465 159 249

IAC#4

585.8 3463 160 188

PrcsdIAC#4

583.2 3462 160 181

End TURN Begin S & L

582.8 3462 160 180

IAC#4

579.4 3462 160 180

PrcsdIAC#4

579.2 3462 160 180

ATC:DSCNDto2000. ft

575.0 3463 159 180

End S & L Begin FLARE
to -3.2 deg

PrcsdChAlt

572.8 3463 159 180

PrcsdChAlt

572.4 3463 159 180

ATCcn

571.6 3463 159 180

AAon

569.0 3457 159 180

IAC#5

559.2 3376 159 179

PrcsdIAC#5

556.6 3339 159 179

End FLARE Begin DSCNT
to 2118.5 ft

556.4 3336 159 179

IAC#5

552.8 3279 160 180

PrcsdIAC#5

552.6 3276 160 180

IACfn

532.6 2979 159 180

ATC:TURN to 120. deg

480.0 2192 160 180

PrcsdTurn

477.8 2160 159 180

PrcsdTurn

Figure 5.6 (cont.)

477.4	2154	159	180				
					ATCcn		
476.6	2142	159	179				
							AA active
476.2	2136	159	179				
							End DSCNT Begin FLARE to 0.0 deg
474.2	2107	159	179				
				AAoff PrcsdAltAl			
473.4	2095	160	179				
							AA inactive
473.2	2092	160	179				
				FACR			
465.0	2004	160	179				
						FACst PrcsdFACR	
464.8	2003	160	179				
						FAC#1	
459.8	1985	160	179				
							End FLARE Begin TURN to 120.0 deg
457.6	1985	160	179				
					PrcsdFAC#1		
457.2	1986	160	178				
					FAC#1		
453.4	1987	160	167				
						PrcsdFAC#1	
453.2	1987	160	166				
							ATC:Cleared to land
450.0	1987	160	156				
				PrcsdClrFL			
448.8	1987	160	153				
					PrcsdClrFL		
447.4	1986	160	149				
					ATCcn		
446.6	1986	160	146				
							End TURN Begin DECEL to 150.0 kts
437.6	1983	160	119				
							End DECEL Begin S & L
427.4	1987	149	120				
				FlapR			
425.8	1987	149	119				
							Flaps at 15.0
					FlapS PrcsdFlapR		
423.2	1987	149	119				
							LOC: on -2.5 dots
412.6	1989	149	120				
					PrcsdLOCon		

Figure 5.6 (cont.)

412.4	1989	149	120				
				PrcsdLOCon			
411.4	1989	149	120				
					Loc A		
411.0	1988	149	120				
							End S & L Begin TURN to 90.0 deg
410.2	1988	149	120				
							GS: on -1.4 dots
409.0	1987	149	119				
					PrcsdGSon		
408.8	1987	149	119				
				GearR			
408.0	1987	149	118				
					GslpA		
407.4	1987	149	118				
							Landing gear down
					GearD PrcsdGearR		
405.0	1985	149	116				
						FAC#2	
404.8	1985	149	116				
				PrcsdGSon			
404.0	1985	149	115				
				PrcsdFAC#2			
400.2	1983	150	112				
				FAC#2			
398.4	1982	150	111				
						PrcsdFAC#2	
398.2	1982	150	111				
							End TURN Begin DECEL to 140.0 kts
369.0	1988	149	89				
							End DECEL Begin DECEL to 139.0 kts
358.8	1986	139	90				
							End DECEL Begin FLARE to -2.5 deg
357.8	1985	138	90				
				FlapR			
357.2	1985	138	90				
				FlapR			
355.2	1984	138	90				
							Flaps at 25.0
					FlapS PrcsdFlapR		
354.6	1983	138	90				
							Flaps at 30.0
					FlapS PrcsdFlapR		
349.2	1968	138	90				

Figure 5.6 (cont.)

						FAC#3	
349.0	1967	138	90				
					PrcsdFAC#3		
343.8	1943	139	90				
					FAC#3		
340.0	1920	139	89				
						PrcsdFAC#3	
339.8	1918	139	89				
							End FLARE Begin DSCNT
329.6	1828	139	90				
						FAC#6	
314.8	1647	139	89				
					PrcsdFAC#6		
312.2	1614	139	89				
							OM active
310.2	1589	139	90				
				PrcsdOMon			
310.0	1587	139	90				
					FAC#6		
308.4	1567	139	90				
					PrcsdOMon		
						PrcsdFAC#6	
308.2	1565	139	90				
							OM inactive
307.8	1560	139	90				
						FACfn	
303.2	1503	139	89				
					AltCo		
261.4	1013	139	89				
				PrcsdAltCo			
260.0	997	139	89				
					AltCo		
216.4	508	139	89				
				PrcsdAltCo			
215.0	493	139	89				
					AltCo		
198.4	314	139	90				
				PrcsdAltCo			
197.0	299	139	90				
							MM Active
					RwisC		
192.2	248	138	90				
				PrcsdMMon			
192.0	246	138	90				
				PrcsdRwisC			
190.6	231	138	90				
					PrcsdMMon		
189.0	214	138	90				
					AltCo		
188.8	212	138	90				

Figure 5.6 (cont.)

					MM inactive
187.8	202	139	90		
				PrcsdAltCo	
187.2	195	139	90		
					End DSCNT Begin DECEL to 134.0 kts
183.2	153	139	90		
					End DECEL Begin DSCNT
172.4	46	133	90		
					End DSCNT Begin FLARE to 0.0 deg
171.4	36	133	90		
					GS off
168.6	14	133	90		
					End FLARE Begin S & L
163.8	1	133	89		

approach, the IAC is completed "late", if we assume that there exists a requirement to complete it prior to leaving the 3500 ft assigned approach altitude.

Later in the descent toward the new assigned altitude of 2000 ft, the high and nominal workload time-lines again parallel one another (i.e., t_{go} = 450s on the nominal corresponds to t_{go} = 480s on the high workload approach). This parallel procedural activity continues through level-out at 2000 ft, and down to GS turn on (t_{go} = 409s on the high workload approach and t_{go} = 326s on the nominal workload approach). At this point considerable procedural activity differences become evident.

In the high workload approach, the turn to final (at t_{go} = 410s) begins relatively close in to the field, with a lateral positioning that places the vehicle slightly more than 2.5 deg off the LOC plane (as measured about the GS transmitter). As noted in Appendix B, this ensures that the GS indicator will be inactive; however, approximately one second later, the vehicle comes to within 2.5 deg of the LOC plane, and the GS indication provides the crew with a GS measurement. Because of the relative closeness to the field, however, the GS indicator does not become active at the customary -3 dots; instead it shows a relatively small -1.4 dot error.

This small error immediately places the crew "behind" in the approach, since the gear should have been dropped at 2 dots low, and the vehicle slowed to 140 kt at 1.5 dots low. The time-line of Figure 5.6 shows an almost immediate gear down request by the PF (at t_{go} = 408s), but this is not acted on immediately since the PNF is busy announcing GS activity (at t_{go} = 407s). To compound matters, the PF cannot initiate the required deceleration to 140 kt until he completes the turn to final, which doesn't occur until t_{go} = 369s.

By this time, the glide slope error has been reduced to less than 0.5 dot, which means that the PF is "behind" in both his required deceleration to the approach speed of 139 kt, and his pitch down to the final glide path. As shown in the time line, he "stacks" both of these commands immediately after ending the turn to final, in an attempt to catch up.

Once having initiated the pitch down (at t_{go} = 358s), two neglected flap requests are made, one which should have been made after the deceleration to 140 kt, and the other after the deceleration to 139 kt. While the PF then concentrates on stabilizing the vehicle on the glide slope, the PNF sets the flaps (at t_{go} = 355s and t_{go} = 349s), and continues with the final approach checklist. Because the late flap requests delay the checklist progress the FAC is not completed until t_{go} = 303s, after

the vehicle has passed through the OM beacon. Thus, in the high workload approach, the FAC is completed "late", if we assume that there exists a requirement to complete it prior to OM activity. Note also that the PNF misses making the OM announcement, because of his preoccupation with the FAC.

Although slightly "late" at this point, the crew has effectively caught up with the nominal workload approach. Thus, the 1000 ft altitude callout is made appropriately (at t_{go} = 261s), and the subsequent callouts by the PNF, and maneuver by the PF, directly parallel those of the nominal workload approach. Note that because of slight numerical differences in the nominal and high workload simulations, the end-points of the two runs differ slightly: the former terminates at zero altitude with a small negative sink rate, while the latter terminates at 1 ft altitude, and begins to "float" down the runway. No attempt has been made to "fine-tune" these differences out of the simulation, since this type of terminal performance is beyond the scope of the current approach to landing study.

5.3.4 Model Parameter Variations

Variations in crew model parameters considered here will affect all aspects of the approach. Inasmuch as the trajectory performance is most likely to be biased by the sample effects

associated with using a particular noise sequence (and by the simplified disturbance model as well), we will refrain from a detailed discussion of this aspect of the simulations. Suffice to say that the high noise cases did result in poorer glide path control on final approach, as expected, and these variations and others had some effect on the final flare, as noted below.

On the other hand, estimation error uncertainty is somewhat less sensitive to sample effects because it depends primarily on noise covariances rather than on the particular noise sample. Table 5.4 gives the standard deviation of the estimation errors of several states (h, V, ψ, γ) at the decision height of 200′. It is clear from these results that increasing disturbances or decreasing attention increases the standard deviation of the estimation error (uncertainty) as expected. Increasing lock-up times has a small effect on PF′s uncertainty and virtually none on that of PNF. There is virtually no effect on uncertainty resulting from the change in the default gains.

The difference in ATC scenario doesn′t have an effect on estimation uncertainty for the nominal configurations (cases #1); there is some difference in the high noise, low attention cases, (# 4) but a consistent trend is not apparent. The differences between MAP and SAP are also not completely consistent except that the effect of changing roles is reflected in the estimation

Table 5.4: Standard Deviation of Estimation Errors at Decision Height

Case #	h(ft)		V(ft/s)		ψ(deg)		γ(deg)	
	PF	PNF	PF	PNF	PF	PNF	PF	PNF
1LS	7.1	5.2	.21	.16	.36	.51	.13	.13
1LM	5.2	6.3	.16	.21	.25	.42	.13	.13
2LS	12.4	10.9	.73	.81	.77	1.24	.53	.59
3LS	7.9	6.3	.24	.16	.41	.61	.15	.14
4LS	14.5	11.4	.77	.81	.92	1.94	.56	.60
4LM	12.3	11.8	.83	.79	.83	1.84	.64	.53
5LS	7.6	5.2	.24	.16	.46	.59	.13	.13
6LS	7.0	5.3	.20	.16	.37	.52	.13	.13
1HS	7.1	5.4	.21	.16	.39	.58	.13	.13
1HM	5.3	6.4	.16	.21	.27	.41	.13	.13
4HS	12.7	12.3	.70	.85	1.48	1.84	.50	.61
4HM	13.1	11.8	.87	.79	.96	1.84	.65	.55

performances of PF and PNF. In addition, it is interesting that, with the exception of the high workload, high noise case, the PF's estimation uncertainty in altitude is reduced for the MAP procedure.

For the most part, the variations investigated did not have major effects on the time-lines. The time-lines for case 3LS did not differ from those of case 1LS, showing that for a small disturbance level and relaxed tempo a significant reduction in attention from high levels is possible. This is both expected and as it should be.

The most striking difference in time-lines with regard to procedural execution occurs near the end of the high disturbance level approaches. As illustrated in Figure 5.7 for case 4LS (similar results are obtained for case 2LS), the deceleration to threshold speed is late (h<100'). Typically, this is not sufficient to cause a missed approach but it could result in a modified landing procedure (not simulated), in which PF would forego decelerating to threshold speed and would increase the final flare rate. The late execution of the deceleration procedure in these cases is due to the larger uncertainty in altitude (see Table 5.4) compounded by a delay in going "heads-up" after hearing the RWIS call.

Figure 5.7 also shows that PNF fails to make the "approaching minimums" callout in the high noise situation. This appears to be the result of the large uncertainty in altitude estimation along with (our) requirement that the PNF be 95% certain of being within 25 ft of the callout altitude before making the callout.

The imposition of longer procedure lock-up times naturally results in a longer time to complete the various procedures.* This does not have any noticeable effect until the very end of the approach. Then, as in the high noise case, the final deceleration is delayed and the landing altered.

The effects of increasing the default gains for control and monitoring were as expected. Control and estimation performance improved slightly. Almost all procedures were executed in timely fashion, though there was some delay associated with the requirement for the other EGP's to exceed .6 (rather than .3) before they could be selected. The one exception is the OM callout which was not made in this case. This miss occurs because the gain for that callout does not exceed .6 before the outer marker turns off.

* Increased lock-up times could also be used to simulate the demands of another (unmodelled) problem.

Figure 5.7: Final Portion of Time Line for High Disturbance Level
(Case 4LS)

				PrcsdAltCo		
105.6	1004	138	89			
					AltCo	
57.2	507	139	89			
				PrcsdAltCo		
55.8	493	139	89			
						MM Active
32.8	255	139	90			
				PrcsdMMon		
32.6	253	139	90			
					RwisC	
32.2	249	138	90			
				PrcsdRwisC		
30.8	235	138	90			
					PrcsdMMon	
29.0	216	138	90			
						MM inactive
28.4	210	139	90			
					AltCo	
27.6	201	139	90			
				PrcsdAltCo		
26.2	187	139	90			
						End DSCNT Begin DECEL to 134.0 kts
23.2	157	139	89			
						GS off
12.2	56	132	90			
						End DECEL Begin DSCNT
10.0	31	132	90			
						End DSCNT Begin FLARE to 0.0 deg
8.4	13	132	90			
						End FLARE Begin S & L
4.4	4	132	90			

The results for crew parameter variations (attention, lock-up time and default gains) indicate that, while PROCRU does exhibit some sensitivity to these variables, there is a desirable degree of latitude in selecting specific values for them.

6. CONCLUDING REMARKS

PROCRU, a new simulation model for analyzing crew procedures in approach to landing, has been described. The model is a system model that can account for vehicle dynamics, environmental disturbances and crew activities in information processing, decision making, control and communication. Crew sub-tasks are defined based on a time-line analysis of nominal procedures. Information processing and control behavior is modelled after the approach utilized in the Optimal Control Model. Decision making behavior is based on maximizing subjective expected gain. The result is a complex, stochastic model for analyzing the impact on approach and landing of system, procedure and crew variables.

The PROCRU model has not been validated experimentally, though the information processing and control parts of it have been tested in manual control experiments. In addition, for this initial implementation, several important aspects of human behavior have been simplified or neglected. Nonetheless, it is likely that even in its present state of development, with some upgrading of wind models and vehicle dynamics, PROCRU could be used to analyze many questions of interest regarding procedures for approach and landing. Candidate areas of application would include:

i) Application of the model to simulation of other approach scenarios. This could include an examination of other high workload radar-vectored approaches, and variations in aircraft configurations (e.g., engine out), ILS beam geometries, runway and terrain elevations, and winds and gusts. Clearly, a large range of scenario parameters could be studied with the facility now provided by the PROCRU model.

ii) Model analysis of procedural variations. This could include analysis of different category landings, given standard operating procedures, and a determination of the impact of procedural variations away from a given standard operating procedural set. By examining variations in time-line activity, crew tempo, monitoring requirements, and trajectory propagation, a model-based evaluation of procedural improvements could be conducted, and thus provide the basis for the potential development of a rational and analytic procedural design methodology.

iii) Analysis of the effects of changes in the cockpit environment resulting from the introduction of various control and display aids. Thus, one could, for example, compare manual and coupled approches or examine the effects of auto throttles, HUD's, etc.

iv) Application of the model to other flight phases, such as takeoff or the touchdown/rollout/braking phase. As in the approach to landing study, an analysis of the impact of various vehicular, procedural, and environmental factors could be conducted, to provide a model-based assessment of crew workload and flight performance variations.

v) Application and validation of the model using detailed NTSB incident and accident reports. By "model-matching" the simulation results to one or more documented case studies, open areas of model implementation could be identified, and modifications proposed to ensure procedural parallels between simulation and actual time-line. In addition, such a modelling effort would provide a means of testing various hypotheses of accident/incident causation, and could directly suggest means of ameliorating or eliminating such causal factors.

There are also many directions for extending and improving PROCRU; some simple, some more complicated. A few of these are discussed below.

In the area of increased model sophistication, a number of potential improvements suggest themselves. By introducing a failure capabilty in the various vehicle subsystems, and providing the crew members with a failure detection and identification logic, abnormal and emergency response models could be studied. Naturally, this would require the specification of additional procedures to handle such situations, but the current model structure is ideally suited to handle this expansion, and the currently available operations handbooks provide a reasonably concise specification of the required procedures.

By continuing an interaction with active flight crew personnel, more sophisticated models of procedural gains could be developed. These could reflect not only the explicit procedural requirements stated in the operations manual, but also the implicit requirements, and the crews' goals, motivation, and experience. We would expect that the model requirements would guide us in our crew queries, and their responses would provide us with additional data for developing more sophisticated and representative procedural gain expressions.

The development and implementation of a more detailed model of out-the-window visual cue processing could provide additional insight concerning the dynamics of runway acquisition, and the impact of different monitoring strategies. Such a model would also

have the potential of providing for gradual acquisition of runway cues, and not be limited to the all-or-none visibility conditions conventionally utilized in ILS approach studies.

Finally, there are several user-oriented improvements that would enhance PROCRU's utility. The addition of a graphical output capabilty and of statistical analysis programs would greatly facilitate the rapid and thorough analyses of approach performance. Modifications to increase computation speed (such as modifying the program to allow variable length integration time steps) would be very useful for reducing the cost of Monte Carlo simulation analysis.

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APPENDIX A: GLOSSARY

A: altitude (ft)

AA: altitude alert

AC: altitude command from ATC (ft)

AE: airport elevation (ft above sea level)

AFE: above field elevation

A/R: as required

ATC: air traffic control

ATIS: airport traffic information service (weather and visibility info)

CAT I: category I landing, with a DH of 200' AFE, and an RVR of 2400 ft

CFL: cleared for landing

CSD: constant speed drive

DH: decision height (ft)

EPR: exhaust pressure ratio setting for engines

FAC: final approach checklist

F/O: First Officer

fpm: feet per minute

G/A: go around

GS: glide slope

GWT: vehicle gross weight

H: heading (deg)

HC: heading command from ATC (deg)

HSI: horizontal situation indicator, driven by localizer beam

IAC: initial approach checklist

ILS: instrument landing system

IM: inner marker

kt: nm/hr

LOC: localizer

LOM: outer marker

MA: missed approach

MAP: missed approach procedure; monitored approach procedure

MM: middle marker

NAV: navigation

nm: nautical mile

OM: outer marker

PF: pilot flying

PNF: pilot not flying

RF: radio frequency

RVR: runway visual range (ft)

RW: runway

SAP: standard approach procedure

SB: speed brake

SH: search height (ft)

S/O: Second Officer

SOP: standard operating procedures

TD: touchdown

V: velocity (kts)

VAPP: desired approach speed, determined by VBUG and wind/gust correction factor

VBUG: bug speed, set on airspeed indicator, and determined by VREF and landing flap choice

VC: velocity command from ATC (kts)

VGUST: gust velocity

VHF: very high frequency

VOR/ADF: VHF omni range/automatic direction finder

VREF: reference speed, determined by vehicle gross weight

VTHRESH: desired speed at RW threshold, determined by VBUG and gust correction factor

VWIND: wind speed

Appendix B: GLIDE SLOPE AND LOCALIZER

B.1 Basic Geometry

Glide slope and localizer geometries are shown in Figure B.1. The runway is assumed to be 10000 ft long, with the glide slope transmitter located 1150 ft beyond runway threshold and the localizer transmitter located 1000 ft beyond the end of the runway. The nominal glide slope is assumed to be 2.5 deg, with a sensitivity of 1 dot/0.35 deg. The localizer is assumed to be aligned along the east-west direction, and to have a sensitivity of 1 dot/deg.

The figure also shows specific above field nominal altitudes along the glide slope, with the corresponding range-to-go, measured in the plane of the runway, and referenced to glide slope transmitter location. The nominal touchdown point is 1140 ft beyond the glide slope transmitter, assuming flare initiation at 50 ft over runway threshold.

B.2 Functional Description

B.2.1 Localizer

Figure B.2 shows a bottom view of the basic localizer geometry, referenced to the local geographic navigation frame (north, east, down). The parameters specifying the geometry are:

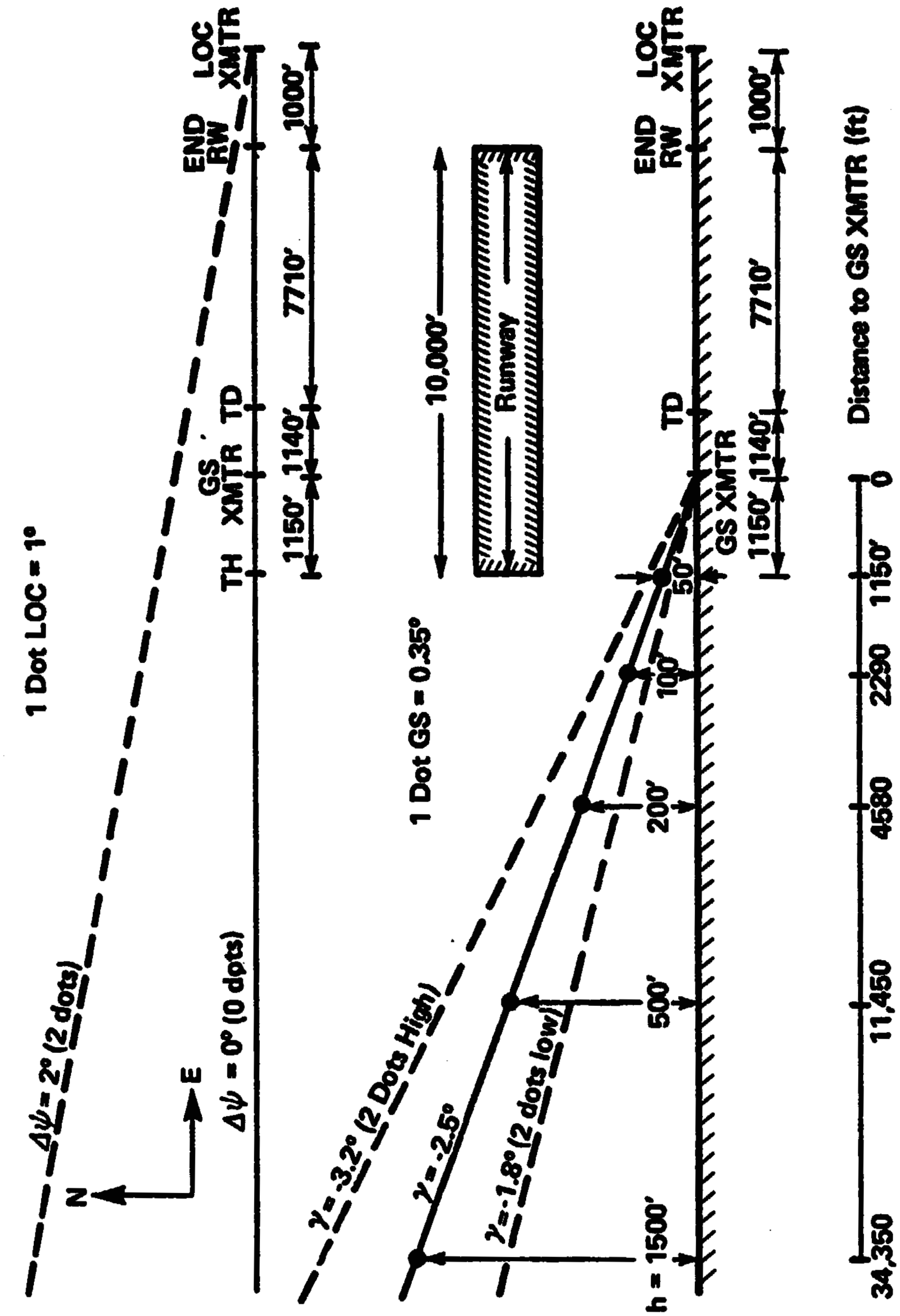

Figure B.1: Glide Slope and Localizer Geometries

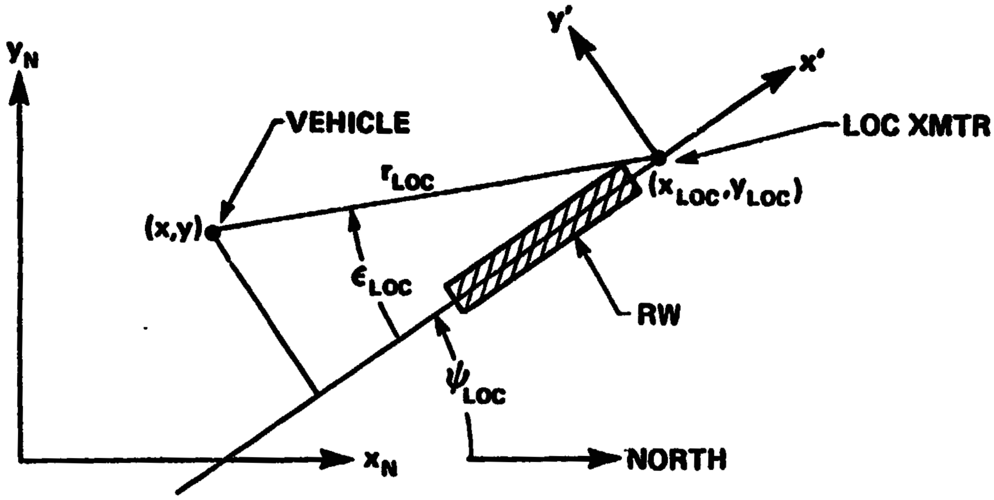

Figure B.2: Basic Localizer Geometry (bottom view)

ψ_{LOC} inbound heading of LOC beam

(x_{LOC}, y_{LOC}) location of LOC transmitter, in N frame coordinates

(x, y) location of vehicle, in N frame coordinates

The prime frame indicated in the figure is the LOC frame, with its origin at the LOC transmitter, and with the x'-axis aligned with the inbound heading. In this coordinate frame, vehicle position is given by:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos \psi_{LOC} & \sin \psi_{LOC} \\ -\sin \psi_{LOC} & \cos \psi_{LOC} \end{bmatrix} \begin{bmatrix} x - x_{LOC} \\ y - y_{LOC} \end{bmatrix} \tag{B.1}$$

Range to the LOC transmitter is then given by

$$r_{LOC} = [(x')^2 + (y')^2]^{1/2} \tag{B.2}$$

and LOC error, as defined in the figure, is given by

$$\varepsilon_{LOC} = \tan^{-1}[y'/(-x')] \tag{B.3}$$

Our model of the localizer assumes minimum and maximum operating ranges, so that if

$$r_{LOC} > r_{LOC}^{max} \quad \text{or} \quad r_{LOC} < r_{LOC}^{min}$$

the localizer is "inactive". A similar angular limit was imposed, so that if

$$\varepsilon_{LOC} > \varepsilon_{LOC}^{max}$$

the localizer is "inactive".

Particular parameters chosen for the nominal geometry are given in Table B.1.

B.2.2 Glide Slope

Figure B.3a shows a bottom view of the basic glide slope geometry, referenced to the local geographic navigation frame. The parameters specifying the geometry are:

ψ_{LOC}	inbound heading of LOC beam
(x_{GS}, y_{GS})	location of GS transmitter, in N frame coordinates
(x, y)	location of vehicle, in N frame coordinates

The double prime frame indicated in the figure is the GS frame, with its origin at the GS transmitter, and with the x''-axis aligned with the inbound heading. In this coordinate frame, vehicle position is given by:

$$\begin{bmatrix} x'' \\ y'' \end{bmatrix} = \begin{bmatrix} \cos\psi_{LOC} & \sin\psi_{LOC} \\ -\sin\psi_{LOC} & \cos\psi_{LOC} \end{bmatrix} \begin{bmatrix} x-x_{GS} \\ y-y_{GS} \end{bmatrix} \quad \text{(B.4)}$$

Range to the GS transmitter is then given by:

Table B.1: Localizer Parameters

Parameter	Value	Dimension
ψ_{LOC}	90	deg
(x_{LOC}, y_{LOC})	(0,9850)	ft
$(r_{LOC}^{min}, r_{LOC}^{max})$	(10,120000)	ft
ϵ_{LOC}^{max}	2.5*	deg

*value used for model simulation; Chapter 2 analysis used 2.0 deg

Table B.2: Glide Slope Parameters

Parameter	Value	Dimension
ψ_{LOC}	90	deg
(x_{GS}, y_{GS})	(0,0)	ft
$(r_{GS}^{min}, r_{GS}^{max})$	(10,90000)	ft
ϵ_{GS}^{max}	2	deg
θ_{GS}	2.5	deg

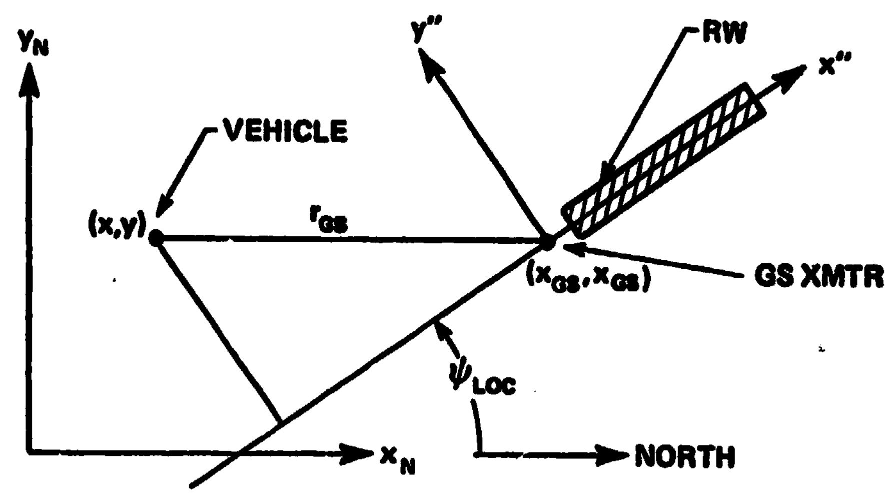

Figure B.3a: Basic Glide Slope Geometry (bottom view)

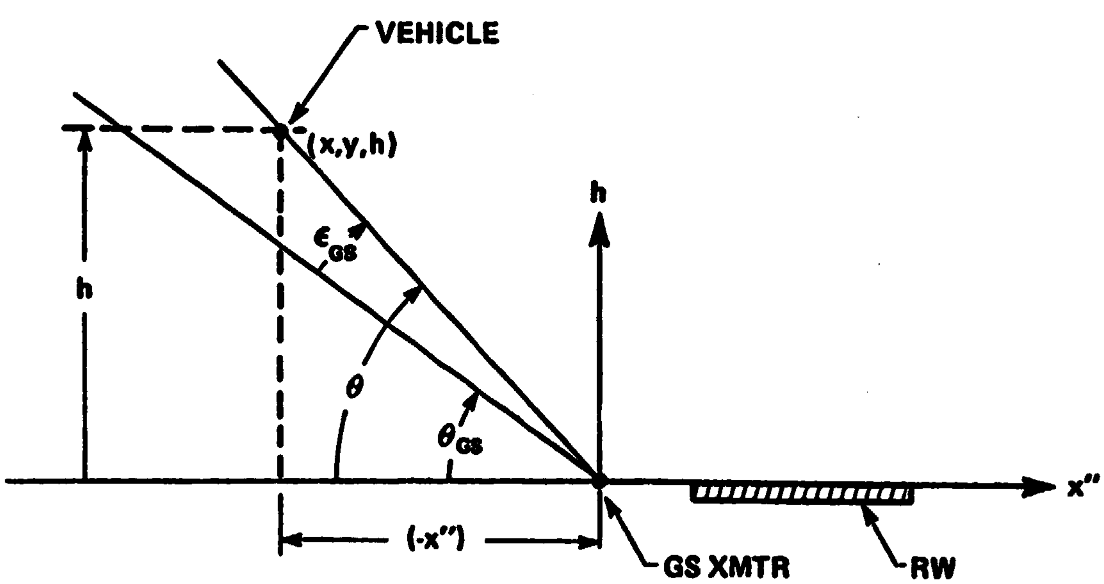

Figure B.3b: Basic Glide Slope Geometry (side view)

$$r_{GS} = [(x'')^2 + (y'')^2]^{1/2} \tag{B.5}$$

Figure B.3b shows a side view of the glide slope geometry. The parameters specifying the geometry are:

θ_{GS} elevation angle of the glide slope

h vehicle altitude AFE

The vehicle elevation angle is given by

$$\theta = \tan^{-1}[h/(-x'')] \tag{B.6}$$

so that the glide slope error, as defined in the figure, is given by

$$\varepsilon_{GS} = \theta - \theta_{GS} \tag{B.7}$$

Our model of the glide slope assumes minimum and maximum operating ranges, so that if

$$r_{GS} > r_{GS}^{max} \quad \text{or} \quad r_{GS} < r_{GS}^{min}$$

the glide slope is "inactive". A similar vertical plane angular limit was imposed, so that if

$$|\varepsilon_{GS}| > \varepsilon_{GS}^{max}$$

the glide slope is "inactive". Finally, a lateral angular limit was implicitly imposed, by not allowing the glide slope to be active until the vehicle was within ε_{LOC}^{max} of the localizer plane, as measured about the glide slope transmitter.

Particular parameters chosen for the nominal geometry are given in Table B.2.

APPENDIX C: VEHICLE DYNAMICS

C.1 Non-Linear Equations of Motion

Assuming the vehicle is a point mass acted upon by aerodynamic and gravitational forces, we can write the following standard equations of motion:

$$m\dot{v} = T\cos\alpha - D - mg\sin\gamma \tag{C.1a}$$
$$mv\cos\gamma\dot{\psi} = (L+T\sin\alpha)\sin\phi \tag{C.1b}$$
$$-mv\dot{\gamma} = -(L+T\sin\alpha)\cos\phi + mg\cos\gamma \tag{C.1c}$$
$$\dot{x} = v\cos\gamma\cos\psi \tag{C.1d}$$
$$\dot{y} = v\cos\gamma\sin\psi \tag{C.1e}$$
$$\dot{z} = -v\sin\gamma \tag{C.1f}$$

where the vehicle "states" are:

v: speed with respect to the local navigation frame
ψ: heading measured clockwise with respect to north
γ: flight path angle measured up from the local horizontal
(x,y,z): vehicle position in the local navigation frame north, east, and down directions.

and where the vehicle "controls" are:

T: thrust (assumed to be along the vehicle's x-axis)
α: angle-of-attack between the vehicle's x-axis and the velocity vector
ϕ: bank angle between the vehicle's y-axis and the local horizontal

The form of the lift and drag forces (L and D) will be discussed in the next section.

If we assume that both angle-of-attack and flight path angle are small (which is the case, as shown in the main text), and replace the vehicle's z-position with the negative of its altitude h, (C.1) then becomes:

$$m\dot{v} = T-D-mg\gamma \tag{C.2a}$$
$$mv\dot{\psi} = (L+T\alpha)\sin\phi \tag{C.2b}$$
$$mv\dot{\gamma} = (L+T\alpha)\cos\phi - mg \tag{C.2c}$$
$$\dot{x} = v\cos\psi \tag{C.2d}$$
$$\dot{y} = v\sin\psi \tag{C.2e}$$
$$\dot{h} = v\gamma \tag{C.2f}$$

C.2 Lift and Drag

The lift and drag forces can be expressed as follows:

$$L = \bar{q}SC_L \tag{C.3a}$$
$$D = \bar{q}SC_D \tag{C.3b}$$

where the reference area S is a fixed constant and where the dynamic pressure is given by

$$\bar{q} = \frac{1}{2}\rho v^2 \tag{C.4}$$

An exponential density model is assumed, so that

$$\rho = \rho_o e^{-h/h_o} \tag{C.5}$$

where

$$\rho_o = 0.002377 \text{ slug/ft}^3 \quad (C.6a)$$
$$h_o = 33{,}333 \text{ ft} \quad (C.6b)$$

The lift and drag coefficients are assumed to have the following functional dependence:

$$C_L = C_L(\alpha, \delta_f) \quad (C.7a)$$
$$C_D = C_D(\alpha, \delta_f, \delta_g) \quad (C.7b)$$

where

α: angle-of-attack
δ_f: flap setting
δ_g: gear setting

In the above functional forms, Mach number dependence has been ignored, because of the relatively small variation in Mach number occurring over the approach and landing trajectories under study. In addition, it is assumed that gear settings have negligible influence on the lift coefficient.

The lift coefficient is assumed to be linear in angle-of-attack, with the flaps contributing in an additive fashion:

$$C_L = C_{L_\alpha}(\alpha - \alpha_z) + C_{L_f} \quad (C.8)$$

where

C_{L_α} : lift coefficient slope (constant)
α_z: zero lift angle-of-attack, for no flaps (constant)

and where the flap contribution is assumed to be proportional to flap setting:

$$C_{L_f} = C_{L_f}^{max} \left(\delta_f/\delta_f^{max}\right) \tag{C.9}$$

where

$C_{L_f}^{max}$: maximum lift contribution from flaps (constant)

δ_f^{max} : maximum flap setting (constant)

Specific lift coefficient parameter values assumed for the current 727 study are summarized in table C.1.

The drag coefficient is assumed to be quadratic in angle-of-attack with the flaps and gear contributing in an additive fashion:

$$C_D = C_{D_O} + n_f C_{L_\alpha}^2 \left(\alpha - \alpha_z\right)^2 + C_{D_f} + C_{D_g} \tag{C.10}$$

where

C_{D_O}: parasite drag (constant)

n_f: drag efficiency factor (constant)

and where the flap contribution is assumed to be proportional to flap setting:

$$C_{D_f} = C_{D_f}^{max} \left(\delta_f/\delta_f^{max}\right) \tag{C.11}$$

Table C.1: Lift Coefficient Parameter Values

Parameter	Value	Dimension
S	1560	ft^2
m	4658	slug
C_{L_α}	5.1	rad^{-1}
α_z	$\begin{cases}-0.175\\-10.0\end{cases}$	$\begin{cases}\text{rad}\\\text{deg}\end{cases}$
$C_{L_f}^{max}$	1.0	--
δ_f^{max}	40	deg

Table C.2: Drag Coefficient Parameter Values

Parameter	Value	Dimension
C_{D_O}	0.040	--
$C_{D_f}^{max}$	0.010	--
$C_{D_g}^{max}$	0.010	--
n_f	0.080	--

where

$C_{D_f}^{max}$: maximum drag contribution from flaps (constant)

The gear contribution is assumed to have the following form:

$$C_{D_g} = \begin{cases} 0 & \text{when } \delta_g = \text{up} \\ C_{D_g}^{max} & \text{down} \end{cases} \tag{C.12}$$

where

$C_{D_g}^{max}$: maximum drag contribution from gear (constant)

Note that the drag coefficient expression (C.10) assumes, for simplicity, that the efficiency factor n_f is independent of flap setting.

Specific drag coefficient parameter values assumed for the current study are summarized in Table C.2.

C.3 Decomposition of States and Controls

Equation sets (C.2) through (C.12) define the vehicle's state output response to a specified set of control inputs. In order to "solve" this non-linear, time-varying set of equations, we make the following set of assumptions:

1. Flap and gear settings, although "inputs" to the system, are not considered available for continuous control of the system. Rather, they are treated as discrete mode configuration variables, which are procedurally defined, and which undergo step changes in their associated settings.

2. Thrust, angle-of-attack, and bank are taken as the available control inputs, and are assumed representable by a constant plus a small perturbation:

$$T = T_C + \delta T \tag{C.13a}$$

$$\alpha = \alpha_C + \delta\alpha \tag{C.13b}$$

$$\phi = \phi_C + \delta\phi \tag{C.13c}$$

where the C subscript indicates a constant and the $\delta(\ )$ indicates a perturbation quantity.

3. The vehicle states are assumed representable by a "nominal" value plus a small perturbation, according to:*

$$v = v_N + \delta v \tag{C.14a}$$

$$\psi = \psi_N + \delta\psi \tag{C.14b}$$

$$\gamma = \gamma_N + \delta\gamma \tag{C.14c}$$

$$x = x_N + \delta x \tag{C.14d}$$

$$y = y_N + \delta y \tag{C.14e}$$

$$h = h_N + \delta h \tag{C.14f}$$

*This notation differs slightly from that in Chapter 3 but the correspondence is evident.

4. The nominal velocity, heading, and flight path angle are chosen to be the sum of specified constant plus rate terms*:

$$v_N = v_c+\dot{v}_c t \tag{C.15a}$$

$$\psi_N = \psi_c+\dot{\psi}_c t \tag{C.15b}$$

$$\gamma_N = \gamma_c+\dot{\gamma}_c t \tag{C.15c}$$

and the nominal altitude is chosen to have an additional (as yet unspecified) constant acceleration term*:

$$h_N = h_c+\dot{h}_c t + \frac{1}{2}\ddot{h}_c t^2 \tag{C.15f}$$

Expressions for the nominal x and y positions will be derived later in section C.5.

The rational for these assumptions and choice of nominals will become evident in our discussion later in section C.6. For now, however, we will use these equation sets to decompose the earlier non-linear dynamic equations into two simpler, and analytically tractable sets: a "nominal" equilibrium set and a linear perturbation set. We begin by decomposing the lift and drag forces.

C.4 Decomposition of Lift and Drag

C.4.1 Dynamic Pressure Expression

Dynamic pressure variations are due to both variations in density and velocity. The density variation is obtained by

* The subscript c denotes a constant value.

substituting (C.15f) into (C.5) to yield:

$$\rho = \rho_o e^{-h_c/h_o} e^{-\dot{h}_c t/h_o} e^{-\frac{1}{2}\ddot{h}_c t^2/h_o}\; e^{-\delta h/h_o} \qquad (C.16)$$

The first exponential term is a constant, so define

$$\rho_c = \rho_o e^{-h_c/h_o} \qquad (C.17a)$$

The second exponential term can be approximated by an expansion. The largest constant-rate altitude change occurring in the trajectory is 6500 ft (see Table 4 of Chapter 2), so that, with (C.6b),

$$|\dot{h}_c t/h_o|_{max} \lesssim 0.2$$

which suggests that a second-order expansion provides an adequate approximation:

$$e^{-\dot{h}_c t/h_o} \simeq 1 - \frac{\dot{h}_c t}{h_o} + \frac{1}{2}\left(\frac{\dot{h}_c t}{h_o}\right)^2 \qquad (C.17b)$$

The third exponential term can also be approximated by an expansion. The largest vertical accelerations occur during a flare to a new flight path angle. If we assume a maximum 1000 ft drop during such a flare, and conservatively attribute all of the drop to the vertical acceleration, then

$$\left|\frac{1}{2}(\ddot{h}_c t^2/h_o)\right|_{max} \lesssim 0.03 << 1$$

so that

$$e^{-\frac{1}{2}\ddot{h}_c t^2/h_o} \simeq 1 - \frac{1}{2}(\ddot{h}_c t^2/h_o) \qquad (C.17c)$$

Finally, since the altitude perturbation is by definition small,

$$e^{-\delta h/h_o} \simeq 1 - \delta h/h_o \tag{C.17d}$$

Substituting (C.17) into (C.16), and dropping cross-product terms involving small quantities, we obtain the following expression for density:

$$\rho = \rho_c \left[1 - \frac{\dot{h}_c t}{h_o} + \frac{1}{2}\left(\frac{\dot{h}_c t}{h_o}\right)^2 - \frac{1}{2}\left(\frac{\ddot{h}_c t^2}{h_o}\right)\right]\left[1 - \frac{\delta h}{h_o}\right] \tag{C.18}$$

The velocity contribution to dynamic pressure is obtained by use of (C.14a) and (C.15a):

$$v^2 = v_c^{\,2}\left[1 + \frac{\dot{v}_c t}{v_c} + \frac{\delta v}{v_c}\right]^2 \tag{C.19}$$

From Table 4 of Chapter 2, it can be seen that the ratio of velocity change ($\dot{v}_c t$) to starting velocity (v_c) is greatest for the 20 kt deceleration starting at 190 kts. Thus,

$$|\dot{v}_c t/v_c|_{max} \simeq 0.11$$

Since the velocity perturbation is by definition small, we can then expand (C.19) to obtain

$$v^2 \simeq v_c^{\,2}\left[1 + \frac{2\dot{v}_c t}{v_c} + \left(\frac{\dot{v}_c t}{v_c}\right)^2 + 2\,\frac{\delta v}{v_c}\right] \tag{C.20}$$

where we have dropped the second-order perturbation term and the cross-product involving the velocity perturbation and the "small" term ($\dot{v}_c t/v_c$).

The dynamic pressure expression can now be found by substituting (C.18) and (C.20) into (C.4), and dropping second-order perturbation terms, cross-product terms involving a perturbation quantity and a "small" time-dependent term, and cross-product terms involving two "rate" terms* (e.g., $\dot{v}_c \dot{h}_c$). The resulting expression is given by:

$$\bar{q} \simeq \bar{q}_c + \bar{q}_c \left[\lambda(t) + 2 \frac{\delta v}{v_c} - \frac{\delta h}{h_o} \right] \tag{C.21}$$

where

$$\bar{q}_c = \frac{1}{2} \rho_c v_c^{\,2} \tag{C.22}$$

and

$$\lambda(t) = \left[2 \left(\frac{\dot{v}_c}{v_c}\right) \cdot \left(\frac{\dot{h}_c}{h_o}\right) \right] t + \left[\left(\frac{\dot{v}_c}{v_c}\right)^2 + \frac{1}{2}\left(\frac{\dot{h}_c}{h_o}\right)^2 - \frac{1}{2}\left(\frac{\ddot{h}_c}{h_o}\right) \right] t^2 \tag{C.23}$$

Note that $\bar{q}$ is expressed as the sum of a constant, a time-varying term, and a term composed of state perturbations.

C.4.2 Lift and Drag Expressions

Lift and drag variations are due to variations in their respective coefficients, and to variations in the dynamic pressure. The coefficient variations are obtained by substituting (C.13b) into (C.8) and (C.10) to yield:

$$C_L = C_{L_\alpha} (\alpha_c - \alpha_z) + C_{L_f} + C_{L_\alpha} \delta\alpha \tag{C.24a}$$

$$C_D = C_{D_O} + n_f\, C_{L_\alpha}^{\,2} (\alpha_c - \alpha_z)^2 + C_{D_f} + C_{D_g} + 2 n_f C_{L_\alpha}^{\,2} (\alpha_c - \alpha_z)\,\delta\alpha \tag{C.24b}$$

*Neglecting the product of two "rate" terms is justified on the basis of maneuver selection discussed later in section C.6, where, if one rate (e.g., $\dot{v}_c$) is non-zero, then all others must be non-zero so that all such "cross products" must be zero.

where the second-order term in $\delta\alpha$ has been dropped from the drag expression. Assuming that the flap and gear settings remain constant, then C_{L_f}, C_{D_f}, and C_{D_g} remain constants, by (C.9), (C.11), and (C.12). If we define the following constant coefficients, then

$$C_{L_c} = C_{L_\alpha}(\alpha_c-\alpha_z) + C_{L_f} \tag{C.25a}$$

$$C_{D_c} = C_{D_o} + n_f \cdot C_{L_\alpha}^2(\alpha_c-\alpha_z)^2 + C_{D_f} + C_{D_g} \tag{C.25b}$$

and assume that both are non-zero, then (C.24) becomes

$$C_L = C_{L_c}\left(1 + \frac{C_{L\alpha}}{C_{L_c}}\delta\alpha\right) \tag{C.26a}$$

$$C_D = C_{D_c}\left(1 + \frac{2n_f C_{L\alpha}^2(\alpha_c-\alpha_z)\delta\alpha}{C_{D_c}}\right) \tag{C.26b}$$

The lift and drag expressions can now be found by substituting (C.21) and (C.26) into (C.3), and dropping second-order perturbation terms, and cross-product terms involving a perturbation and the "small" quantity $\lambda(t)$. The resulting approximations are given by:

$$L = L_c + L_c\left[\lambda(t) + 2\frac{\delta v}{v_c} - \frac{\delta h}{h_o} + \frac{C_{L\alpha}}{C_{L_c}}\delta\alpha\right] \tag{C.27a}$$

$$D = D_c + D_c\left[\lambda(t) + 2\frac{\delta v}{v_c} - \frac{\delta h}{h_o} + \frac{2n_f C_{L_\alpha}^2(\alpha_c-\alpha_z)}{C_{D_c}}\delta\alpha\right] \tag{C.27b}$$

where

$$L_c = \bar{q}_c S C_{L_c} \tag{C.28a}$$

$$D_c = \bar{q}_c S C_{D_c} \tag{C.28b}$$

Note that both lift and drag are expressed as the sum of a constant, a time-varying term, and a term composed of state and control perturbations.

C.5 Decomposition of Equations of Motion

We now proceed to decompose the non-linear equation set defined by (C.2), using the control variable expressions of (C.13), the state variable representations of (C.14) and (C.15), and the lift and drag relations of (C.27).

The velocity equation of (C.2a) is expanded by use of (C.13), (C.14), (C.15), and (C.27b), to yield, after rearrangement, the following expression:

$$m(\dot{v}_c + g\,\gamma_c) + D_c - T_c = -m\delta\dot{v} - \left(\frac{2D_c}{v_c}\right)\delta v - mg\delta\gamma + \left(\frac{D_c}{h_o}\right)\delta h + \delta T - d_c\delta\alpha - mg\dot{\gamma}_c t - D_c\,\lambda(t) \tag{C.29}$$

where, for convenience, we have defined

$$d_c = 2\bar{q}_c S n_f C^2_{L_\alpha}(\alpha_c - \alpha_z) \tag{C.30a}$$

Note that the RHS of (C.29) is composed of time-functions and perturbation quantities. If we consider the special case where the perturbation quantities are zero at t=0, then, from (C.23), the RHS must be zero. But the LHS is a constant. Thus, both sides must be zero for all time:

$$\dot{v}_c = \frac{1}{m}(T_c - D_c) - g\gamma_c \tag{C.31a}$$

$$\delta\dot{v} = -\left(\frac{2D_c}{mv_c}\right)\delta v - g\delta\gamma + \left(\frac{D_c}{mh_o}\right)\delta h_o + \frac{1}{m}\delta T - \left(\frac{dc}{m}\right)\delta\alpha - f_v(t) \quad \text{(C.32a)}$$

where, for convenience, we have defined

$$f_v(t) = g\dot{\gamma}_c t + \left(\frac{D_c}{m}\right)\lambda(t) \quad \text{(C.33a)}$$

Note that we now have an "equilibrium" solution for the original velocity equation of (C.2a), and an associated first-order perturbation relation.

The heading equation of (C.2b) can be expanded by use of (C.13), (C.14), (C.15), and (C.27a). Terms involving the cross-product of a "small" time function (e.g., $\dot{v}_c t/v_c$) and a perturbation are dropped, as are terms involving the cross products of two "rate" terms* (e.g., $\dot{v}_c\dot{\psi}_c$). After neglecting second-order perturbation products, using small angle approximations, and rearranging, the following expression is obtained:

$$\begin{aligned} mv_c\dot{\psi}_c - (L_c + T_c\alpha_c)\sin\phi_c = {} & -mv_c\delta\dot{\psi} + \left(\frac{2Lc}{v_c}\sin\phi_c - m\dot{\psi}_c\right)\delta v \\ & - \left(\frac{Lc}{h_o}\sin\phi_c\right)\delta h \\ & + \alpha_c\sin\phi_c\delta T + (\ell_c + T_c)\sin\phi_c\,\delta\alpha \\ & + (L_c + T_c\alpha_c)\cos\phi_c\,\delta\phi \\ & + L_c\sin\phi_c\,\lambda(t) \end{aligned} \quad \text{(C.34)}$$

where, for convenience, we have defined

$$\ell_c = \bar{q}_c S C_{L_\alpha} \quad \text{(C.30b)}$$

*See section C.6 for justification of this last simplification.

By the same argument as before, both sides of (C.34) must be zero, so that the following "equilibrium" and perturbation relations result:

$$\dot{\psi}_c = \frac{1}{mv_c}(L_c + T_c\alpha_c)\sin\phi_c \tag{C.31b}$$

$$\delta\dot{\psi} = \left(\frac{2L_c\sin\phi_c}{mv_c^2} - \frac{\dot{\psi}_c}{v_c}\right)\delta v - \left(\frac{L_c\sin\phi_c}{mv_c ho}\right)\delta h + \left(\frac{\alpha_c\sin\phi_c}{mv_c}\right)\delta T$$
$$+ \frac{(\ell_c + T_c)\sin\phi_c}{mv_c}\delta\alpha + \frac{(L_c + T_c\alpha_c)\cos\phi_c}{mv_c}\delta\phi + f_\psi(t) \tag{C.32b}$$

where, for convenience, we have defined

$$f_\psi(t) = \frac{L_c\sin\phi_c}{mv_c}\lambda(t) \tag{C.33b}$$

The flight path equation of (C.2c) can be expanded by use of (C.13), (C.14), (C.15), and (C.27a). Following the same type of simplification and decomposition used for the heading equation, we obtain the following "equilibirium" and perturbation relations:

$$\dot{\gamma}_c = \frac{1}{mv_c}(L_c + T_c\alpha_c)\cos\phi_c - g/v_c \tag{C.31c}$$

$$\delta\dot{\gamma} = \left(\frac{2L_c\cos\phi_c}{mv_c} - \frac{\dot{\gamma}c}{v_c}\right)\delta v - \left(\frac{L_c\cos\phi_c}{mv_c ho}\right)\delta h + \left(\frac{\alpha_c\cos\phi_c}{mv_c}\right)\delta T$$
$$+ \frac{(\ell_c + T_c)\cos\phi_c}{mv_c}\delta\alpha - \frac{(L_c + T_c\alpha_c)\sin\phi_c}{mv_c}\delta\alpha + f_\gamma(t) \tag{C.32c}$$

where, for convenience, we have defined

$$f_\gamma(t) = \frac{L_c \cos\phi_c}{m v_c} \cdot \lambda(t) \tag{C.33c}$$

The ground track equations (C.2d) and (C.2e), specifying x and y vehicle position, can be expanded by use of (C.14) and (C.15), simplified by using small angle approximations and neglecting second-order perturbation terms, and rearranged to yield the following expressions:

$$\dot{x}_N - (v_c+\dot{v}_c t)\cos(\psi_c+\dot{\psi}_c) = -\delta\dot{x} + \cos(\psi_c+\dot{\psi}_c t)\,\delta v \tag{C.35a}$$

$$- (v_c+\dot{v}_c t)\sin(\psi_c+\dot{\psi}_c t)\,\delta\psi$$

$$\dot{y}_N - (v_c+\dot{v}_c t)\sin(\psi_c+\dot{\psi}_c t) = -\delta\dot{y} + \sin(\psi_c+\dot{\psi}_c t)\,\delta v$$

$$+ (v_c+\dot{v}_c t)\cos(\psi_c+\dot{\psi}_c t)\,\delta\psi \tag{C.35b}$$

We can now specify the nominal (x,y) position by requiring the LHS of the above equations to be zero, so that

$$\dot{x}_N(t) = (v_c+\dot{v}_c t)\cos(\psi_c+\dot{\psi}_c t) \tag{C.36a}$$

$$\dot{y}_N(t) = (v_c+\dot{v}_c t)\sin(\psi_c+\dot{\psi}_c t \tag{C.36b}$$

To solve these equations, we must specify $\dot{v}_c$ and $\dot{\psi}_c$. We defer this specification and subsequent solution for (x_N, y_N) until the next section, where we place constraints on the choice of $\dot{v}_c$ and $\dot{\psi}_c$.

c-3

Since the satisfaction of (C.36) implies that the RHS of (C.35) will be zero, it follows that the perturbation relations are given by:

$$\delta\dot{x} = + \cos(\psi_c+\dot{\psi}_c t)\delta v - (v_c+\dot{v}_c t) \sin (\psi_c+\dot{\psi}_c t)\delta\psi \qquad (C.32d)$$

$$\delta\dot{y} = \sin (\psi_c+\dot{\psi}_c t)\delta v + (v_c+\dot{v}_c t)\cos(\psi_c+\dot{\psi}_c t)\delta\psi \qquad (C.32e)$$

Note that, in general, the coefficients are time-varying.

The altitude equation of (C.2f) can be expanded by use of (C.14) and (C.15). Using the same simplifications used in the heading equation derivation, we obtain, after rearrangement, the following relation:

$$\dot{h}_c-v_c\gamma_c = (-\ddot{h}_c+v_c\dot{\gamma}_c+\dot{v}_c\gamma_c)t -\delta\dot{h}+v_c\delta\gamma +\gamma_c\delta v \qquad (C.37)$$

Using the same arguments as before, both sides of the equation must be zero, so that

$$\dot{h}_c = v_c\gamma_c \qquad (C.31f)$$

If we are free to specify the acceleration term $\ddot{h}_c$, we can choose it so that the time function in the RHS is zero:

$$\ddot{h}_c = v_c\dot{\gamma}_c+\dot{v}_c\gamma_c \qquad (C.38)$$

With the RHS of (C.37) zero, this implies that

$$\delta\dot{h} = v_c\delta\gamma +\gamma_c\delta v \qquad (C.32f)$$

This completes the decomposition of the vehicle equations defined in (C.2). To summarize, we have defined the states and controls in terms of nominal and perturbation variables (via (C.13) and (C.14)), defined the nominal variables in terms of specified maneuver rates (via (C.15) and (C.36)), determined the "equilibrium" conditions which give rise to these maneuver rates (via (C.31)), and defined the perturbation relations associated with each state variable (via (C.32)).

C.6 Definition of Nominal Trajectory Segments

Before proceeding with the equation development, it is convenient, at this point, to introduce the notion of nominal trajectory "segments" and their associated "maneuvers".

We assume that the vehicle is constrained to a small set of "maneuvers", representative of the type of maneuvers typically used to effect an ILS approach and landing:

1. S & L : straight and level flight, at constant speed
2. DECEL : constant deceleration flight, at constant heading and flight path angle
3. TURN : constant rate turning, at constant speed and altitude
4. FLARE : constant rate of change of flight path angle, at constant speed and heading
5. DSCNT constant sink rate, at constant speed and heading

We define a nominal trajectory "segment" as that portion of the trajectory associated with the execution of one of the above maneuvers. A segment starts when one of the above maneuvers is

initiated, and ends when a new maneuver is initiated. The entire trajectory is thus considered to be generated by a successive concatenation of appropriate segments.

Table C.3 shows how the maneuver rates of each trajectory segment are defined in terms of segment type and desired maneuver rates. The (constant) maneuver rates are identified with the subscript c, and correspond with the rate terms defining the nominals of (C.15). The (constant) desired maneuver rates are identified with the subscript d, and are assumed to be specified by the procedural rules associated with a given segment. Thus, to define maneuver rates for the four state variables shown, one simply specifies the segment type and the desired maneuver rate for that segment.

Table C.3: Specification of Nominal Maneuver Rates

Maneuver Rate \ Segment Type	S&L	DECEL	TURN	FLARE	DSCNT
$\dot{v}_c$	0	$\dot{v}_d$	0	0	0
$\dot{\psi}_c$	0	0	$\dot{\psi}_d$	0	0
$\dot{\gamma}_c$	0	0	0	$\dot{\gamma}_d$	0
$\dot{h}c$	0	*	0	*	$\dot{h}_d$

* unspecified; see discussion accompanying Table C.4.

Table C.4 defines the resulting time histories for the six nominal states, for each of the five segments. The table presumes that the time origin is coincident with the start of a segment; each state variable at that time is designated by a subscript c (e.g., $v_c = v_N(t=0)$). Nominal variables which remain at their initial values are shown explicitly in the table; those which require an equation for their definition have an equation number entry referring to the set of accompanying equations.

In effect, table C.4 provides an analytic integration of the nominal equations of motion, for each of the specialized maneuvers under consideration. The basis for the expressions shown is given briefly below.

The nominal velocity v_N stays at its initial value v_c, unless the segment is DECEL. In that case v_N is given by (C.15a).

The nominal heading ψ_N stays at its initial value ψ_c, unless the segment is TURN. In that case ψ_N is given by (C.15b).

The nominal flight path angle γ_N is zero during the S&L and TURN segments, and stays at its initial value γ_c during a DECEL segment. During a FLARE segment, γ_N is given by (C.15c). During a DSCNT segment, the climb rate $\dot{h}_c$ is specified, and the nominal velocity v_N equals v_c. The nominal flight path angle is thus found from (C.31f).

The rate of change of nominal ground track position is given by (C.36). During the S&L, FLARE, and DSCNT segments, the vehicle is neither turning nor accelerating, so that $\dot{v}_c$ and $\dot{\psi}_c$ are zero,

Table C.4: Nominal Trajectory Variables

Trajectory Variable \ Segment Type	S & L	DECEL	TURN	FLARE	DSCNT
v_N	v_c	(T1)	v_c	v_c	v_c
ψ_N	ψ_c	ψ_c	(T2)	ψ_c	ψ_c
γ_N	0	γ_c	0	(T3a)	(T3b)
(x_N, y_N)	(T4a)	(T4b)	(T4c)	(T4a)	(T4a)
h_N	h_c	(T5a)	h_c	(T5b)	(T5c)

$$v_N = v_c + \dot{v}_c t \tag{T1}$$

$$\psi_N = \psi_c + \dot{\psi}_c t \tag{T2}$$

$$\gamma_N = \gamma_c + \dot{\gamma}_c t \tag{T3a}$$

$$\gamma_N = \dot{h}_c / v_c \tag{T3b}$$

$$\left.\begin{aligned} x_N &= x_c + (v_c \cos\psi_c) t \\ y_N &= y_c + (v_c \sin\psi_c) t \end{aligned}\right\} \tag{T4a}$$

$$\left.\begin{aligned} x_N &= x_c + \cos\psi_c [v_c + \dot{v}_c t/2] t \\ y_N &= y_c + \sin\psi_c [v_c + \dot{v}_c t/2] t \end{aligned}\right\} \tag{T4b}$$

$$\left.\begin{aligned} x_N &= x_c + (v_c/\dot{\psi}_c) [\sin(\psi_c + \dot{\psi}_c t) - \sin\psi_c] \\ y_N &= y_c - (v_c/\dot{\psi}_c) [\cos(\psi_c + \dot{\psi}_c t) - \cos\psi_c] \end{aligned}\right\} \tag{T4c}$$

$$h_N = h_c + \gamma_c [v_c + \dot{v}_c t/2] t \tag{T5a}$$

$$h_N = h_c + v_c [\gamma_c + \dot{\gamma}_c t/2] t \tag{T5b}$$

$$h_N = h_c + \dot{h}_c t \tag{T5c}$$

and (C.36) integrates to (T4a) of the table. During the DECEL segemnt, $\dot{\psi}_c$ is zero, so that (C.36) integrates to (T4b). Likewise, during the TURN segment, $\dot{v}_c$ is zero, so that (C.36) integrates to (T4c).

The nominal altitude h_N is given by (C.15f):

$$h_N = h_c+\dot{h}_c t + \frac{1}{2}\ddot{h}_c t^2 \tag{C.15f}$$

where, from(C.31f) and (C.38),

$$\dot{h}_c = v_c \gamma_c \tag{C.31f}$$

$$\ddot{h}_c = v_c \dot{\gamma}_c + \dot{v}_c \gamma_c \tag{C.38}$$

During the S&L and TURN segments, both $\dot{h}_c$ and $\ddot{h}_c$ are zero, so that h_N stays at its initial value h_c. During the DECEL segment, $\ddot{h}_c$ is given by $\dot{v}_c \gamma_c$, so, with (C.15f), (T5a) of the table follows directly. Likewise, during the FLARE segment, $\ddot{h}_c$ is given by $v_c \dot{\gamma}_c$, so, with (C.15f), (T5b) follows directly. Finally, during the DSCNT segment, both $\dot{v}_c$ and $\dot{\gamma}_c$ are zero, so that $\ddot{h}_c$ is zero, and (C.15f) implies (T5c).

C.7 Solution for Nominal Controls

With the nominal maneuvers now defined, we may proceed to solve for the nominal control values (thrust, angle-of-attack, and bank) required to satisfy the "equilibirium" conditions defined earlier and summarized in (C.31).

For convenient reference, we restate those conditions:

$$\dot{v}_c = \frac{1}{m}(T_c - D_c) - g\gamma_c \tag{C.31a}$$

$$\dot{\psi}_c = \frac{1}{mv_c}(L_c + T_c\alpha_c)\sin\phi_c \tag{C.31b}$$

$$\dot{\gamma}_c = \frac{1}{mv_c}(L_c + T_c\alpha_c)\cos\phi_c - g/v_c \tag{C.31c}$$

To solve for the required bank angle, we note that if the segment is a TURN, then $\dot{\gamma}_c$ must be zero (recall Table C.3). From (C.31b) and (C.31c), it then follows that

$$\phi_c = \tan^{-1}\left(\frac{v_c\dot{\psi}_c}{g}\right) \tag{C.39}$$

If the segment is <u>not</u> a TURN, then $\dot{\psi}_c$ must be zero (again, from Table C.3). Assuming non-zero lift, (C.31b) then implies that ϕ_c is zero. Consequently, (C.39) above applies whether or not the segment is a TURN; i.e., for all segments.

To solve for the required angle-of-attack, we note from (C.31a) that

$$T_c = D_c + mg(\dot{v}_c/g + \gamma_c) \tag{C.40}$$

so that

$$L_c + T_c\alpha_c = (L_c + D_c\alpha_c) + mg(\alpha_c\dot{v}_c/g + \alpha_c\gamma_c)$$

Substitution into (C.31c) yields

$$L_c+D_c\alpha_c = \frac{mg}{\cos\phi_c}\left[1 + \frac{v_c\dot{\gamma}_c}{g} - \frac{\alpha_c\dot{v}_c}{g}\cos\phi_c - \alpha_c\gamma_c\cos\phi_c\right] \quad (C.41)$$

But with $\dot{v}_c$ on the order of 1kt/sec, and α_c on the order of 1 deg,

$$\left|\frac{\alpha_c\dot{v}_c}{g}\cdot\cos\phi_c\right| < \left|\frac{\alpha_c\dot{v}_c}{g}\right| \lesssim 0.001$$

and with γ_c on the order of 1 deg,

$$\left|\alpha_c\gamma_c\cos\phi_c\right| < \left|\alpha_c\gamma_c\right| \lesssim 0.0005$$

so that the last two terms of the RHS of (C.41) are effectively second-order "small" terms, which can be dropped. Expansion of the LHS, via (C.25) and (C.28), and rearrangement, then yields the following cubic in α_c:

$$\alpha_c^3 + a\alpha_c^2 + b\alpha_c + c = 0 \quad (C.42)$$

where the constant coefficients are given by:

$$a = -2\alpha_z \quad (C.43a)$$

$$b = \alpha_z^2 + (C_{L_\alpha} + C_{D_O} + C_{D_f} + C_{D_g})/(n_f C^2 L_\alpha) \quad (C.43b)$$

$$c = [C_{L_f} - C_{L_\alpha}\alpha_z - \frac{mg}{\bar{q}_c S\cos\phi_c}(1 + v_c\dot{\gamma}_c/g)]/(n_f C^2 L_\alpha) \quad (C.43c)$$

and where $\bar{q}_c$ is given by (C.17a) and (C.22).

With the angle-of-attack thus specified, the corresponding thrust level is specified by (C.40) above, where D_c is defined by (C.25), (C.28), and the value of α_c.

It is appropriate to note that although (C.39), (C.40), and (C.42) define the appropriate constant controls for each of the trajectory segments of interest, they are "trim" controls, in the conventional sense, only for the S&L, TURN, and DSCNT segments. For the DECEL and FLARE segments, they are more appropriately labelled "maneuver trim" controls.

C.8 Perturbation Equations

With the nominal trajectory variables and their associated "trim" controls now defined, we may conveniently summarize the perturbation equations derived earlier.

If we define the perturbation state and control vectors as follows,

$$\underline{x} = [\delta v, \delta\psi, \delta\gamma, \delta h, \delta x, \delta y]^T \tag{C.44a}$$

$$\underline{u} = [\delta T, \delta\alpha, \delta\phi] \tag{C.44b}$$

then (C.32) may be rewritten as

$$\dot{\underline{x}} = A\,\underline{x} + B\,\underline{u} + \underline{z}(t) \tag{C.45}$$

The state and control matrices are given by:

$$A = \left[\begin{array}{cc:c} \multicolumn{2}{c:}{A_{44}} & \\ \hdashline A_{22} & \multicolumn{1}{:c:}{O_{22}} & O_{62} \end{array}\right] \qquad B = \left[\begin{array}{c} B_{33} \\ \hdashline O_{33} \end{array}\right] \tag{C.46}$$

where O_{62}, O_{22}, and O_{33} are (6x2), (2x2), and (3x3) zero matrices, and

$$A_{44} = \begin{bmatrix} -2D_c/mv_c & 0 & -g & D_c/mh_o \\ \left[\dfrac{2L_c\sin\phi_c}{mv_c^2} - \dfrac{\dot{\psi}_c}{v_c}\right] & 0 & 0 & -\left[\dfrac{L_c\sin\phi_c}{mv_ch_o}\right] \\ \left[\dfrac{2L_c\cos\phi_c}{mv_c{}^2} - \dfrac{\dot{\gamma}_c}{v_c}\right] & 0 & 0 & -\left[\dfrac{L_c\cos\phi_c}{mv_ch_o}\right] \\ \gamma_c & 0 & v_c & 0 \end{bmatrix} \tag{C.47a}$$

$$A_{22} = \begin{bmatrix} \cos(\psi_c+\dot{\psi}_ct) & -(v_c+\dot{v}_ct)\sin(\psi_c+\dot{\psi}_ct) \\ \sin(\psi_c+\dot{\psi}_ct) & (v_c+\dot{v}_ct)\cos(\psi_c+\dot{\psi}_ct) \end{bmatrix} \tag{C.47b}$$

$$B_{33} = \begin{bmatrix} 1/m & -d_c/m & 0 \\ \dfrac{\alpha_c\sin\phi_c}{mv_c} & \dfrac{\sin\phi_c}{mv_c}(\ell_c+T_c) & \dfrac{\cos\phi_c}{mv_c}(L_c+T_c\alpha_c) \\ \dfrac{\alpha_c\cos\phi_c}{mv_c} & \dfrac{\cos\phi_c}{mv_c}(\ell_c+T_c) & \dfrac{-\sin\phi_c}{mv_c}(L_c+T_c\alpha_c) \end{bmatrix} \tag{C.47c}$$

The constant controls appearing in the above matrices (T_c, α_c, ϕ_c) are defined by the appropriate equations of the previous section. The lift and drag terms (L_c, D_c) are defined by (C.22), (C.25) and (C.28); their corresponding sensitivities (ℓ_c, d_c) are defined by (C.22) and (C.30). The time-driven perturbation input of (C.45) is obtained from (C.33) and is given by:

$$\underline{z}(t) \equiv \begin{bmatrix} \frac{-D_c}{m}\,\lambda(t) - g\dot{\gamma}_c t \\ 0 \\ \frac{L_c \cos\phi_c}{mv_c}\,\lambda(t) \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{C.48}$$

where $\lambda(t)$ is defined by (C.23). It should be noted that the second component of the $\underline{z}$ vector is shown as zero, rather than the general $f_\psi(t)$ expression given by (C.33b). This is justified on the following basis. If the vehicle is on a TURN segment, then Table C.3 and (C.23) require that $\lambda(t)$ be zero, so that $f_\psi(t)$ is zero. If the vehicle is not on a TURN segment, then the bank angle is zero, so that again (C.33b) requires $f_\psi(t)$ to be zero. Thus, $f_\psi(t)$ is zero for all segments considered.

Three points should be made regarding the state equation of (C.45). First, the ordering of the components of the state and control vectors is arbitrary; the particular ordering of the state vector given by (C.44a), with δh preceeding δx and δy, was chosen to emphasize the fact that δx and δy have no driving effects

on the state (as demonstrated by the O_{62} matrix of (C.46)). The second point concerns the time-invariance. A_{44} and B_{33} are time-invariant, whereas A_{22} is time-invariant only when the vehicle is not in a TURN segment. Thus, B is always time-invariant, and A is likewise whenever a TURN is not being executed. Finally, the perturbation input $\underline{z}$ only drives the speed and flight path angle states, and is directly attributable to variations in dynamic pressure with changes in these variables.

APPENDIX D: MODEL FOR EXTERNAL VISUAL CUEING

Our model of external visual cue processing is based on the notion that the pilot utilizes perspective geometric cues for inferring changes in vehicle state. The use of this type of cue was studied and modelled by Wewerinke [4] in his aircraft landing study; our model is essentially a direct generalization of his approach.

D.1 Perspective Geometric Modelling

We assume that the essential features of the external visual scene can be abstracted by a relatively simple perspective line drawing. In particular, for the approach to landing task under consideration, we assume that the nominal out-the-window view available to the crew can be schematized as shown in Figure D.1. Six line elements characterize this visual scene: the horizon (H), the far (F) and near (N) runway ends, the left (L) and right (R) runway edges, and the runway centerline (C).

We further assume that the essential cues provided to the pilot by a display of this sort consists of changes in line element orientation, length, and displacement. As shown in Figure D.2a, the line element orientation angle ν is assumed to be measured with respect to an arbitrary reference contained in the viewing plane and fixed to the vehicle; the (positive counterclockwise) perturbation in orientation $\delta\nu$ is the pilot's corresponding line element orientation cue. Figure D.2b illustrates line length ξ and the corresponding length change cue $\delta\xi$; both are assumed to be expressed in angular units, subtended at the pilot's viewing position. Finally, Figure D.2c illustrates the line element displacement cue $\delta\eta$, defined in a direction normal to the line element and in the viewing plane; as with line length changes, displacements are assumed to be measured in subtended angular units.

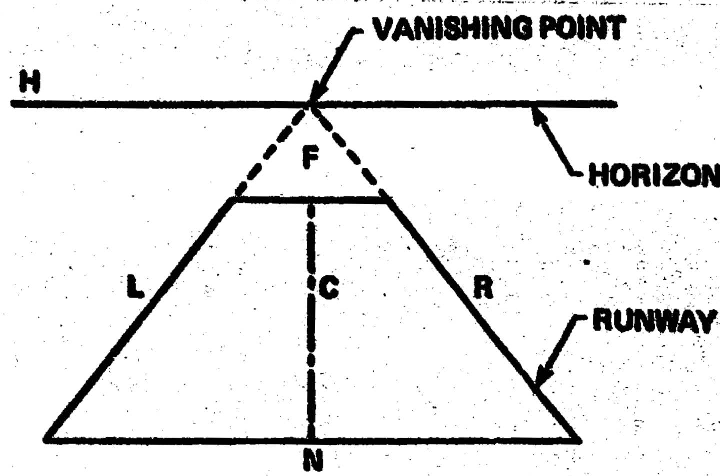

Figure D.1: Visual Cue Dependence on Vehicle State Perturbations

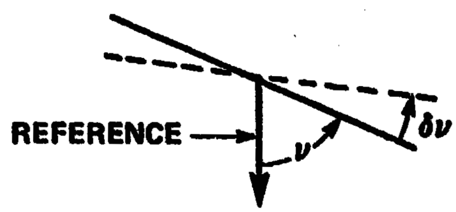

Figure D.2a: Line Element Orientation Cue

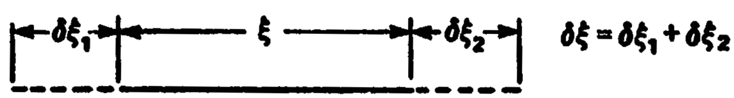

Figure D.2b: Line Element Length Cue

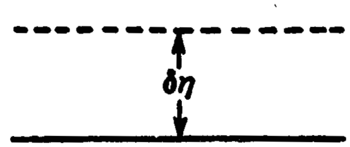

Figure D.2c: Line Element Displacement Cue

These cues arise because of changes in scene perspective, which, in turn, are due to changes in the relative attitude and/or position of the vehicle with respect to the visual objects (in this case, the runway and horizon). To find the functional dependence of these cues on vehicle state, we first define a vehicle state vector*, consisting of vehicle attitude and position:

$$\underline{x}_v \equiv [\phi,\theta,\psi,x',y',h]^T \tag{D.1}$$

where (ϕ,θ,ψ) are the conventional roll, pitch, and yaw vehicle attitude angles, h is vehicle altitude above the field , and (x',y') is vehicle ground position measured in the glide slope coordinate reference system. From Appendix B,

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\psi_{LOC} & \sin\psi_{LOC} \\ -\sin\psi_{LOC} & \cos\psi_{LOC} \end{bmatrix} \begin{bmatrix} x-x_{GS} \\ y-y_{GS} \end{bmatrix} \tag{D.2}$$

where ψ_{LOC} and (x_{GS},y_{GS}) define the glide slope system, and (x,y) is vehicle ground position in the local navigation system.

With this definition of vehicle state, we can now use the basic rules of perspective geometry to derive the functional relation between vehicle state and the "attributes" of the ith line element in the visual scene:

$$(\nu_i,\xi_i,\eta_i) = \underline{f}(\underline{x}_v,\underline{p}_i) \tag{D.3}$$

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*Note that this state vector is not to be confused with the one defined in Appendix C and the main text; it is defined here solely for the purpose of defining the available visual cues.

where $\underline{f}$ is a three-dimensional non-linear function which depends on the parameter vector $\underline{p}_i$ characterizing the ith element of the object being viewed (e.g., runway length, width, etc.).

By assuming perturbations in vehicle state $\delta\underline{x}_v$ this can be linearized to obtain the desired expression for the ith visual cue set:

$$(\delta\nu_i, \delta\xi_i, \delta\eta_i) = \underline{f}_{LIN}(\delta\underline{x}_v, \underline{p}_i) \tag{D.4}$$

where $\underline{f}_{LIN}$ is the appropriately linearized version of $\underline{f}$ above. This function effectively dictates how visual cues arise because of state changes in the vehicle.

D.2 Definition of Visual Cue Set

This general approach was applied to analyze the visual scene sketched in Figure D.1. It was assumed that the vehicle is located nominally at some point along the ILS glideslope, with zero nominal pitch and roll altitude, and with a nominal yaw attitude which coincides with the inbound localizer heading. The result of the analysis is summarized in Table D.1, which shows, for each line element, how each cue depends on the vehicle state perturbations. Terms appearing in the table which have not yet been introduced are defined in the following paragraphs.*

The far and near end range parameters (ℓ_F, ℓ_N) are approximated by the ground track range to the far and near runway ends:

*Entries indicated with an asterisk correspond to fairly complicated expressions, which, as the discussion below points out, have no direct relevance to the present analysis.

Table D.1: Visual Cue Dependence on Vehicle State Perturbations

Line Element \ Visual Cue	$\delta\nu$	$\delta\xi$	$\delta\eta$
H: Horizon	$-\delta\phi$		$-\delta\theta$
F: Far End	$-\delta\phi$	$\frac{2}{\rho_F}\sin\frac{\xi_F}{2}\delta x'$	$-\delta\theta-\delta h/\ell_F$
N: Near End	$-\delta\phi$	$\frac{2}{\rho_N}\sin\frac{\xi_N}{2}\delta x'$	$-\delta\theta-\delta h/\ell_N$
C: Center Line	$-\delta\phi+\delta y'/h_N$	$\frac{1}{\ell_C}\tan\frac{\xi_C}{2}\delta x'$	$-\delta\psi+\delta y'/\ell_C$
L: Left edge	$-\delta\phi+\frac{1}{h_N}[(\cos^2\nu_L\delta y'-\frac{1}{2}\sin 2\nu_L\delta h]$	*	*
R: Right edge	$-\delta\phi+\frac{1}{h_N}[(\cos^2\nu_R\delta y'-\frac{1}{2}\sin 2\nu_R\delta h]$	*	*

$$\ell_F \approx |x'-x'_F| \qquad \text{(D.5a)}$$

$$\ell_N \approx |x'-x'_N| \qquad \text{(D.5b)}$$

where x'_F and x'_N are the along-runway locations of the far and near edges. From Appendix B,

$$x'_F = 1140 \text{ ft} + 7710 \text{ ft} = 8850 \text{ ft} \qquad \text{(D.6a)}$$

$$x'_N = -1150 \text{ ft} \qquad \text{(D.6b)}$$

The center-line range parameter ℓ_c is a composite range, given by

$$\ell_c = \left(\frac{1}{\ell_F} + \frac{1}{\ell_N} \right)^{-1} \qquad \text{(D.5c)}$$

The line-of-sight range parameters (ρ_F, ρ_N) specify the line-of-sight range between the vehicle and the runway corners, and are given by:

$$\rho_F = (W^2+\ell^2_F)^{1/2} \qquad \text{(D.7a)}$$

$$\rho_N = (W^2+\ell^2_N)^{1/2} \qquad \text{(D.7b)}$$

where W specifies half the runway width, and, for our study is assumed given by

$$W = 75 \text{ ft} \qquad \text{(D.6c)}$$

The nominal orientation angles associated with the left and right runway edges are given by

$$\nu_L = \tan^{-1}(W/h_N) \tag{D.8a}$$

$$\nu_R = -\tan^{-1}(W/h_N) \tag{D.8b}$$

where h_N is the nominal vehicle altitude (note that the subscript denotes "nominal" and not "near").

The nominal line segment lengths associated with the far and near runway ends are given by

$$\xi_F = 2\tan^{-1}(W/\ell_F) \tag{D.9a}$$

$$\xi_N = 2\tan^{-1}(W/\ell_N) \tag{D.9b}$$

and the nominal center line length is given by

$$\xi_C = \cos^{-1}\left\{\frac{1}{2\ell_F\ell_N}\left(\ell^2{}_F+\ell^2{}_N-L^2{}_{RW}\right)\right\} \tag{D.9c}$$

where the runway length is given by

$$L_{RW} = 10{,}000 \text{ ft} \tag{D.6d}$$

D.3 Simplified Visual Cue Set

With six line segments comprising the external view, and a potential of three cues per segment, a potential set of 18 cues becomes available for inferring vehicle position and attitude.* To simplify the analysis, we shall arbitrarily limit the number of cues to be considered to six, to correspond with the number of states which the pilot is attempting to infer. We do this by:

a) eliminating from consideration redundant cues;

b) eliminating from consideration cues which are not simple functions of the vehicle state perturbations; and

c) selecting between similar competing cues on the basis of cue sensitivity.

The discussion in the following paragraphs applies these simplifications to the cue set defined in Table D.1.

From Table D.1, the H, F, and N segments all provide a roll cue. Arbitrarily choose the H cue from among this redundant set:

$$\delta\nu_H = -\delta\phi \qquad \text{(D.10a)}$$

Only the H segment provides a pitch cue which is unconfounded by other vehicle perturbations, so choose it:

*Table D.1 shows 17 such cues, since the line element associated with the horizon undergoes no length change.

$$\delta\eta_H = -\delta\theta \tag{D.10b}$$

The C, L, and R segments all provide a yaw cue (confounded with lateral displacement), but the C segment involves the simplest functional dependence. Thus, choose

$$\delta\eta_C = -\delta\psi + \delta y'/\ell_C \tag{D.10c}$$

All segments, except for the horizon, provide a surge cue. The L and R segments confound surge with other vehicle perturbations, so eliminate them from consideration. The F, N, and C segments all provide a surge cue which is unconfounded, so choose the one with the highest sensitivity to surge variations. It is a direct matter to show that this is the N segment, so choose

$$\delta\xi_N = \left(\frac{2}{\rho_N}\sin\frac{\xi_N}{2}\right)\delta x' \tag{D.10d}$$

The C, L, and R segments all provide a sway cue (confounded with roll), but the C segment involves the simplest functional dependence. Thus, choose

$$\delta\nu_C = -\delta\phi + \delta y'/h_N \tag{D.10e}$$

All segments, except for the H and C segments, provide an altitude cue. The L and R segments do not provide a simple functional dependence, so eliminate them from consideration. Of the remaining F and N segments, the N segment provides the greatest sensitivity to altitude variations, so choose

$$\delta\eta_N = -\delta\theta - \delta h/h_N \tag{D.10f}$$

D.4 Display Equation

We may now define a cue, or "display" vector comprised of the above six selected cues:

$$\delta \underline{y} \equiv [\delta\nu_H, \delta\eta_H, \delta\eta_C, \delta\xi_N, \delta\nu_C, \delta\eta_N]^T \tag{D.11}$$

To relate this display vector to the state and control variables introduced in Chapter 3 and Appendix C, we note from (D.2) that

$$\begin{bmatrix} \delta x' \\ \delta y' \end{bmatrix} = \begin{bmatrix} \cos\psi_{LOC} & \sin\psi_{LOC} \\ -\sin\psi_{LOC} & \cos\psi_{LOC} \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \end{bmatrix} \tag{D.12a}$$

and recall that

$$\theta = \gamma + \alpha \tag{D.13}$$

so that

$$\delta\theta = \delta\gamma + \delta\alpha \tag{D.12b}$$

Substitution of (D.12) into (D.10) then yields the following display equation for the external visual cues:

$$\delta \underline{y} = C\delta \underline{x} + D\delta \underline{u} \tag{D.14}$$

where $\delta \underline{y}$ is defined by (D.11), $\delta \underline{x}$ and $\delta \underline{u}$ are defined by (C.44) of Appendix C, and C and D are defined as follows:

$$C \equiv \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & \left(-\frac{1}{\ell_C}\sin\psi_{LOC}\right) & \left(\frac{1}{\ell_C}\cos\psi_{LOC}\right) \\ 0 & 0 & 0 & 0 & \left(\frac{2}{\rho_N}\sin\frac{\xi_N}{2}\cos\psi_{LOC}\right) & \left(\frac{2}{\rho_N}\sin\frac{\xi_N}{2}\sin\psi_{LOC}\right) \\ 0 & 0 & 0 & 0 & \left(-\frac{1}{h_N}\sin\psi_{LOC}\right) & \left(\frac{1}{h_N}\cos\psi_{LOC}\right) \\ 0 & 0 & -1 & -\frac{1}{h_N} & 0 & 0 \end{bmatrix} \qquad (D.15a)$$

$$D \equiv \begin{bmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{bmatrix} \qquad (D.15b)$$

The parameters of the C matrix are, in turn, defined by (D.5) through (D.9) given earlier. This then defines the form and parameters of the display equation associated with the external visual scene.

D.5 Visual Thresholds

As discussed in the text, all display elements have associated with them an effective threshold which limits the accuracy of the display measurement. For the visual display vector just defined, three thresholds are of interest: rotational (ν), extensional (ξ), and displacement (η).

Based on Wewerinke's [4] earlier psychophysical and model-matching work, we assume the rotational threshold to be on the order of a degree visual arc, so that

$$\delta\nu_{TH} = 1 \text{ deg} \qquad \text{(D.16a)}$$

The extensional threshold is assumed to be driven by discriminability limitations, and, on that basis, we choose it in accordance with the Weber-Flechner Law [11]. Specifically, we assume the threshold to be set at a fixed fraction of the total nominal line segment length, or

$$\delta\xi_{TH} = \xi_N/30 \qquad \text{(D.16b)}$$

where the fractional value is chosen to be consistent with an earlier analysis of visual cue processing [12].

The displacement threshold could be set on the basis of maximum human visual activity, which appears to be on the order of 1 minute of arc [13]. However, we feel that this is much too optimistic for a dynamic multi-task situation. A more reasonable value is that associated with Wewerinke's [4] work, approximately one-half degree visual arc, so that

$$\delta\eta_{TH} = 0.5 \text{ deg} \qquad \text{(D.16c)}$$

These thresholds act on each component of the display vector defined in (D.11), with a direct correspondence between cue type and threshold type. That is, (D.16a) applies to δy_1 and δy_5 of (D.11), (D.16b) applies to δy_4, and (D.16c) applies to δy_2, δy_3, and δy_6.